JULIA A. OLSON (OR Bar 062230)
julia@ourchildrenstrust.org
Our Children's Trust
1216 Lincoln Street
Eugene, OR 97401
Tel: (415) 786-4825

ANDREA K. RODGERS (OR Bar 041029)
andrea@ourchildrenstrust.org
Our Children's Trust
3026 NW Esplanade
Seattle, WA 98117
Tel: (206) 696-2851

PHILIP L. GREGORY (*pro hac vice*)
pgregory@gregorylawgroup.com
Gregory Law Group
1250 Godetia Drive
Redwood City, CA 94062
Tel: (650) 278-2957

Attorneys for Plaintiffs

UNITED STATES DISTRICT COURT

DISTRICT OF OREGON – EUGENE DIVISION

KELSEY CASCADIA ROSE JULIANA; **XIUHTEZCATL TONATIUH M.**, through his Guardian Tamara Roske-Martinez; **ALEXANDER LOZNAK**; **JACOB LEBEL**; **ZEALAND B.**, through his Guardian Kimberly Pash-Bell; **AVERY M.**, through her Guardian Holly McRae; **SAHARA V.**, through her Guardian Toña Aguilar; **KIRAN ISAAC OOMMEN**; **TIA MARIE HATTON**; **ISAAC V.**, through his Guardian Pamela Vergun; **MIKO V.**, through her Guardian Pamela Vergun; **HAZEL V.**, through her Guardian Margo Van Ummersen; **SOPHIE K.**, through her Guardian Dr. James Hansen; **JAIME B.**, through her Guardian Jamescita Peshlakai; **JOURNEY Z.**, through his Guardian Erika Schneider; **VIC B.**, through his Guardian Daisy Calderon; **NATHANIEL B.**, through his Guardian Sharon Baring; **AJI P.**, through his Guardian Helaina Piper; **LEVI D.**, through his Guardian Leigh-Ann Draheim; **JAYDEN F.**, through her Guardian Cherri Foytlin; **NICHOLAS V.**, through his Guardian Marie Venner; and **FUTURE GENERATIONS**, through their Guardian Dr. James Hansen;

Plaintiffs,

Case No.: 6:15-cv-01517-AA

[Proposed] SECOND AMENDED COMPLAINT FOR DECLARATORY AND INJUNCTIVE RELIEF

Constitutional Rights; Declaratory Judgment Action (28 U.S.C. §§ 1331, 2201, 2202)

vs.

The UNITED STATES OF AMERICA; **The OFFICE OF THE PRESIDENT OF THE UNITED STATES**; **BRENDA MALLORY**, in her official capacity as Director of Council on Environmental Quality; **SHALANDA YOUNG**, in her official capacity as Acting Director of the Office of Management and Budget; **ERIC LANDER**, in his official capacity as Director of the Office of Science and Technology Policy; **The UNITED STATES DEPARTMENT OF ENERGY**; **JENNIFER GRANHOLM**, in her official capacity as Secretary of Energy; **The UNITED STATES DEPARTMENT OF THE INTERIOR**; **DEB HAALAND**, in her official capacity as Secretary of Interior; **The UNITED STATES DEPARTMENT OF TRANSPORTATION**; **PETE BUTTIGIEG**, in his official capacity as Secretary of Transportation; **The UNITED STATES DEPARTMENT OF AGRICULTURE**; **THOMAS J. VILSACK**, in his official capacity as Secretary of Agriculture; **The UNITED STATES DEPARTMENT OF COMMERCE**; **GINA RAIMONDO**, in her official capacity as Secretary of Commerce; **The UNITED STATES DEPARTMENT OF DEFENSE**; **LLOYD AUSTIN**, in his official capacity as Secretary of Defense; **The UNITED STATES DEPARTMENT OF STATE**; **ANTONY BLINKEN**, in his official capacity as Secretary of State; **The UNITED STATES ENVIRONMENTAL PROTECTION AGENCY**; **MICHAEL REGAN**, in his official capacity as Administrator of the EPA;

Defendants.

TABLE OF CONTENTS

INTRODUCTION

1. For over fifty years, the United States of America[1] has known that carbon dioxide ("CO_2") pollution from burning fossil fuels was causing global warming and dangerous climate change, and that continuing to burn fossil fuels would destabilize the climate system on which present and future generations of our nation depend for their wellbeing and survival. Defendants also knew the harmful impacts of their actions would significantly endanger Plaintiffs, with the damage persisting for millennia. Despite this knowledge, Defendants continued their policies and practices of allowing the exploitation of fossil fuels. Specifically, Department of Energy has approved the export of liquefied natural gas ("LNG") from the Jordan Cove LNG terminal in Coos Bay, Oregon. This export terminal will be the largest projected source of CO_2 emissions in Oregon, and will significantly increase the harm that Defendants' actions are causing to Plaintiffs. Defendants have long-standing knowledge of the cumulative danger that their national energy system, and the aggregate actions taken thereunder, are causing Plaintiffs. The Jordan Cove project enhances the cumulative danger caused by Defendants' affirmative aggregate actions.

2. In a 1965 White House Report on "Restoring the Quality of Our Environment," for example, the President's Science Advisory Committee stated: "The land, water, air and living things of the United States are a heritage of the whole nation. They need to be protected for the benefit of all Americans, both now and in the future. The continued strength and welfare of our nation depend on the quantity and quality of our resources and on the quality of the environment in which our people live."

---

[1] Throughout this Complaint, the terms "United States" or "Federal Government" refer to Defendant United States of America. Alternatively, "U.S." refers to the country, not the Defendant.

3. The United States Environmental Protection Agency ("EPA") in 1990 and the Congressional Office of Technology Assessment in 1991 prepared plans to significantly reduce our nation's CO_2 emissions, stop global warming, and stabilize the climate system for the benefit of present and future generations. Both the EPA's 1990 Plan, "Policy Options for Stabilizing Global Climate," and the OTA's 1991 Plan, "Changing By Degrees: Steps to Reduce Greenhouse Gases," were prepared at the request of, and submitted to, Congress. Despite the imminent dangers identified in both the EPA's 1990 Plan and the OTA's 1991 Plan, Defendants never implemented either plan.

4. Since 1990, Defendants have known that CO_2 levels in the atmosphere must be stabilized at or below 350 parts per million ("ppm") in order to protect our nation's climate system and that a swift transition away from fossil fuels was necessary. Twenty-five years later, today's best science confirms that 350 ppm is the maximum safe level of atmospheric CO_2 required to restore a stable climate system.

5. Defendants have for decades ignored experts they commissioned to evaluate the danger to our Nation, as well as their own plans for stopping the dangerous destabilization of the climate system. Specifically, Defendants have known of the unusually dangerous risks of harm to human life, liberty, and property that would be caused by continued fossil fuel burning. Instead, Defendants have willfully ignored this impending harm. By their exercise of sovereign authority over our country's atmosphere and fossil fuel resources, they permitted, encouraged, and otherwise enabled continued exploitation, production, and combustion of fossil fuels, and so, by and through their aggregate actions and omissions, Defendants deliberately allowed atmospheric CO_2 concentrations to escalate to levels unprecedented in human history, resulting in a dangerous destabilizing climate system for our country and these Plaintiffs.

6. The 1965 Report and the 1990 and 1991 Plans are only examples of the extensive knowledge Defendants have had about the dangers they caused to present and future generations, including Plaintiffs. Since 1965, numerous other studies and reports also have informed Defendants of the significant harms that would be caused if Defendants did not reduce reliance on carbon-intense energy from fossil fuels and rapidly transition to carbon-free energy. These studies and reports concluded that continued fossil fuel dependency would drive the atmospheric concentration of CO_2 to dangerous levels that would destabilize the climate system.

7. Yet, rather than implement a rational course of effective action to phase out carbon pollution, Defendants have continued to permit, authorize, and subsidize fossil fuel extraction, development, consumption and exportation – activities producing enormous quantities of CO_2 emissions that have substantially caused or substantially contributed to the increase in the atmospheric concentration of CO_2. Through its policies and practices, the Federal Government bears a higher degree of responsibility than any other individual, entity, or country for exposing Plaintiffs to the present dangerous atmospheric CO_2 concentration. In fact, the United States is responsible for more than a quarter of global historic cumulative CO_2 emissions.

8. The present level of CO_2 and its warming, both realized and latent, are already in the zone of danger. Defendants have acted with deliberate indifference to the peril they knowingly created. As a result, Defendants have infringed on Plaintiffs' fundamental constitutional rights to life, liberty, and property. Defendants' acts also discriminate against these young citizens, who will disproportionately experience the destabilized climate system in our country.

9. By and through natural gas imports and exports, the Federal Government and the Department of Energy are further enhancing the dangerous climate situation, without due process

and in violation of Plaintiffs' right to equal protection. As noted above, the Jordan Cove LNG Terminal in Coos Bay, Oregon, is the sole LNG export terminal in the Northwest and Oregon's largest projected source of CO_2 emissions. The Department of Energy's approval of LNG exports from the Jordan Cove LNG Terminal heightens the danger to Plaintiffs that Defendants' actions in the aggregate have created. The result is an unconstitutional violation of Plaintiffs' fundamental rights.

10. Plaintiffs are especially vulnerable to the dangerous situation that Defendants have substantially caused. This Court is Plaintiffs' last resort to ensure their reasonable safety, and that of our Posterity, from the harm perpetrated by Defendants. There is an extremely limited amount of time to preserve a habitable climate system for our country; otherwise, the warming of our nation will become locked in or rendered increasingly severe. Recent scientific studies conclude that our country is now in a period of "carbon overshoot," with early consequences that are already threatening and that will, in the short term, rise to unbearable unless Defendants take immediate action to rapidly abate fossil fuel emissions and restore energy balance at a lower atmospheric CO_2 concentration.

11. The current policies, plans, and practices of the Federal Government will not achieve even a proportionate share of the fossil fuel emission reductions that must occur within this century. To the contrary, Defendants' policies, plans, and practices permit, authorize, and subsidize fossil fuel exploitation and consumption, and thus press our climate system further toward irretrievable impacts. A key recent instance is the government's approval of LNG exports from the Jordan Cove LNG Terminal. If Defendants continue to promote such development and further delay rapid, systematic annual emissions reductions, they will ensure a far less hospitable climate system, with far-reaching damage to our nation and Plaintiffs alike.

12. This Court should issue a declaratory judgment to resolve this actual constitutional case and controversy between these young Plaintiffs and the government Defendants as to whether Defendants' national energy system has violated and continues to violate Plaintiffs' Fifth Amendment rights as described herein. Until the Court resolves this constitutional controversy, these young Plaintiffs will continue to be harmed and put at extreme risk by Defendants' energy system and Defendants will continue policies and practice, made up of many aggregate actions, to perpetuate an unconstitutional energy system, avoiding the constitutional check of Article III courts and undermining the separation of powers that the Framers intended. Without declaratory relief in the first instance, Defendants will be free to, and will, continue their policies and practices that make the nation's energy system in a manner that "may hasten an environmental apocalypse" and carry out "the Nation's willful destruction." Declaratory judgment will eliminate the current and substantial legal controversy and inform the parties of the unlawfulness or lawfulness of the government's conduct, especially as to whether Defendants' conduct causes a deprivation of rights secured by the Constitution. It has long been held that there is an expectation in our democracy that government officials will comply with a declaratory judgment. *Utah v. Evans*, 536 U.S. 452, 463-64 (2002). If the constitutional controversy is resolved in their favor by declaratory judgment, Plaintiffs intend to seek further relief as deemed appropriate and consistent with the separation of powers between the three branches of government. Plaintiffs come before this Court to defend and secure their fundamental rights under the Constitution, before it is too late.

JURISDICTION AND VENUE

13. This action is brought pursuant to the United States Constitution. It is authorized by Article III, Section 2, which extends the federal judicial power to all cases arising in equity

under the Constitution. An actual case and controversy exists between Plaintiffs and Defendants because Defendants have established and carried out a national energy system, through policies, practices and aggregate actions, that Plaintiffs claim cause a deprivation of their rights of equal protection, substantive due process, and public trust. An actual case and controversy exists because, while Plaintiffs claim Defendants' national energy system causes Plaintiffs' individual and particularized injuries that rise to a constitutional violation, Defendants deny that their national energy system is unconstitutional and that they are thereby causing a deprivation of Plaintiffs' rights secured by the Constitution. This controversy not only threatens Plaintiffs' lives and liberties, but threatens the very existence of our Republic until it is resolved by our Article III courts. The resolution of that controversy involves questions of scientific, historic, and other factual evidence. Plaintiffs have no adequate remedy at law to redress the harms herein, which are of a continuing nature and which, if left unresolved, will be irreversible.

14. This Court has jurisdiction pursuant to 28 U.S.C. § 1331 (federal question) as this action arises under the laws of the United States. This Court can grant declaratory relief in the first instance and later consider further necessary or proper relief, if warranted, pursuant to the Declaratory Judgment Act. 28 U.S.C. §§ 2201, *et seq.* Specifically, "[i]n a case of actual controversy within its jurisdiction, [ ] any court of the United States, upon the filing of an appropriate pleading, may declare the rights and other legal relations of any interested party seeking such declaration, whether or not further relief is or could be sought. Any such declaration shall have the force and effect of a final judgment or decree and shall be reviewable as such." 28 U.S.C. § 2201. "Further necessary or proper relief based on a declaratory judgment or decree may be granted, after reasonable notice and hearing, against any adverse party whose rights have been determined by such judgment." 28 U.S.C. § 2202. Only the Court has the

authority to declare a government system unconstitutional. No other branch of government can do that. Declaring the United States national energy system to be unconstitutional would resolve the controversy between the parties, thereby redressing a substantial cause of Youth Plaintiffs' constitutional injuries and minimizing and eliminating a source of their significant risk of sustaining worsening injuries.

15. Venue lies in this judicial district by virtue of 28 U.S.C. § 1391(e). The majority of Youth Plaintiffs (as hereinafter defined) reside in this judicial district, some Defendants have offices in this judicial district, and the events, omissions, and harms giving rise to the claims herein arise in substantial part in this judicial district. Pursuant to Local Rule 3-2, divisional venue lies in the Eugene Division because the largest number of Youth Plaintiffs reside in this division of the judicial district, and events, omissions, and harms giving rise to the claims herein arise in substantial part in this division of the judicial district.

PLAINTIFFS

16. Plaintiff **Kelsey Cascadia Rose Juliana** is a citizen of the U.S. and a resident of Eugene, Oregon. Kelsey is 19 years old and was born and raised in Oregon, the state where she hopes to work, grow food, recreate, have a family, and raise children. During the fall of 2014, Kelsey walked 1,600 miles from Nebraska to Washington D.C. in the Great March for Climate Action to raise awareness about the climate crisis. Kelsey is harmed by Defendants' actions and inactions regarding carbon pollution and the resulting climate destabilization and ocean acidification. Specifically, Defendants' actions have caused damage to and continue to threaten the resources on which she relies for her survival and wellbeing. Kelsey depends on the freshwaters of Oregon for drinking, hygiene, and recreation. She drinks the freshwater that flows from the McKenzie River and drinks from springs in the Oregon Cascades on hiking,

canoeing, and backpacking trips. Kelsey also depends upon the marine and estuarine waters of Oregon as a food source and a place of recreation and vacationing. Kelsey spends time along the Oregon coast in places like Yachats and Florence and enjoys playing on the beach, tidepooling, and observing unique marine animals. An important part of Kelsey's diet includes food that comes from the marine waters and freshwater rivers, including salmon, cod, tuna, clams, mussels, and crab. Kelsey also depends upon food grown in Oregon both by small farmers in the Willamette Valley and by her family in their garden.

17. The current and projected drought and lack of snow caused by Defendants are already harming all of the places Kelsey enjoys visiting, as well as her drinking water, and her food sources—including wild salmon. During the summer of 2015, record-setting heat and low water levels killed salmon in Oregon's rivers. In the coming decades, Kelsey will suffer even greater harm from the impacts of ocean acidification and rising sea levels on the marine life she eats for sustenance, and on the beaches, tidepools, and other places she visits along the Oregon coast.

18. In addition to coastal recreation, Kelsey enjoys snowshoeing, cross-country skiing, and snow camping. Warmer winters and declining snowpack make it harder for her to enjoy these winter activities. Kelsey also enjoys rafting, swimming in rivers, snorkeling on rivers, canoeing on lakes, hiking, rock-climbing, and backpacking in the warmer seasons. Increasing summer temperatures, and the resulting algal blooms in the lakes Kelsey visits harm her ability to enjoy these activities and prevent her from drinking the water. Intense wildfires, which also threaten Kelsey's ability to enjoy summer activities. Kelsey has had to abandon camping trips because of nearby wildfires.

19. Defendants have caused psychological and emotional harm to Kelsey as a result of her fear of a changing climate, her knowledge of the impacts that will occur in her lifetime, and her knowledge that Defendants are continuing to cause harms that threaten her life and wellbeing. As a result of the acts and omissions of Defendants, Kelsey believes that she will not be able to continue to do all of the things described in this Complaint for her life, health, and enjoyment, nor will she one day be able to share those experiences with her children.

19-A. Kelsey's individual injuries to her water and food sources, her personal security and safety, her mental wellbeing, her freedom to live, travel, recreate, safely raise children and pursue happiness in her home state of Oregon, are already occurring. Defendants' national energy system is a substantial cause of those actual injuries.

a. Defendants' national energy system worsens Kelsey's individual injuries each year. Kelsey is additionally injured by each passing year of losing the ability to prevent the worsening of her injuries. Kelsey is also injured by each passing year of losing the ability to prevent the irreversibility and inevitability of a lifetime of worsening hardship to her water and food sources, her personal security and safety, her mental wellbeing, her freedom to live, travel, recreate, safely raise children, and pursue happiness in her home state of Oregon. The further loss of the ability to protect her life, while suffering these harms, is a separate concrete psychological, emotional, and mental health injury to Kelsey. Another separate injury is the deprivation of Kelsey's ability to act in her own interest to preserve the window of opportunity to prevent irreversible and inevitable injury going forward and therefore protect her life, all the while suffering these ongoing harms each year from Defendants' national energy system, which Defendants know is

causing these injuries. The opportunity to prevent irreversible and inevitable injuries is still available now and is being progressively foreclosed by the ongoing national energy system. When the irreversibility of these harms becomes certain, redress will be forever foreclosed by this Court or the political majority through the ballot box. Thus, Kelsey's injuries stem precisely from Defendants' belief, and resultant policies and practices, that the national energy system is constitutionally compliant.

b. Every attempt Kelsey makes to safeguard her life, liberties, property, and equal protection of the law fails because Defendants view the national energy system as constitutionally compliant. As long as Defendants operate under the belief that the national energy system is constitutionally compliant, Defendants will continue to power it with fossil fuels at levels that are dangerous for Kelsey and which foreclose her ability to obtain relief that will protect herself. The composition of the United States national energy system is the most important factor in the world as to whether Kelsey can prevent her irreversible injury. If the national energy system remains predominantly fossil fuel-based, Kelsey will permanently lose her ability to obtain relief that will protect herself and her rights.

c. If this Court should issue a declaratory judgment to resolve this actual constitutional case and controversy between these young Plaintiffs and these government Defendants as to whether Defendants' national energy system has violated and continues to violate Plaintiffs' constitutional rights as described herein, the Court will have ordered a change in legal status that would have practical consequences. A declaratory judgment would significantly increase the

likelihood that Kelsey would obtain relief to safeguard her life, liberty, property, and equal protection of the law. If the Court declares the nation's energy system unconstitutional in its present form, Defendants will correct the unconstitutional policies and practices of the national energy system. The worsening of Kelsey's injuries at the hands of her government will end, providing substantially meaningful partial redress of her injuries. The Court will thereby preserve Kelsey's opportunity to obtain relief to safeguard her life, liberty, property, and equal protection of the law from irreversible and inevitable injury. Protecting the opportunity for freedom and happiness and safety and security, by eliminating a substantial federal government restraint on freedom and decreasing the substantial risk of irreversibility, is tremendously meaningful redress.

20. Plaintiff **Xiuhtezcatl Tonatiuh M.**, by and through his guardian and mother Tamara Roske-Martinez, is a 15-year-old citizen of the U.S. who lives in Boulder, Colorado. For nine years, Xiuhtezcatl has advocated for reductions in CO_2 emissions before local, state, federal, and international governmental bodies, including three speeches before the United Nations, and service on the Presidential Youth Council to advise the President of the United States. As the youth director for his organization Earth Guardians, Xiuhtezcatl uses music, dance, art, videos, speeches, testimony, and youth organizing to urge his governments to stop taking actions that promote fossil fuel exploitation and result in dangerous climate change.

21. Of Aztec descent, Xiuhtezcatl engages in sacred indigenous spiritual and cultural practices to honor and protect the Earth. Xiuhtezcatl has suffered harm to his spiritual and cultural practices from Defendants' actions. Climate change also harms Xiuhtezcatl's personal safety, property, and recreational interests through the resulting increased frequency and

intensity of wildfires, drought, declining snowpack, pine-beetle infested forests, and extreme flooding near his home in Colorado. Xiuhtezcatl's home, including the forests that he relies upon for his spiritual, physical, emotional, and mental wellbeing, will continue to die and burn as climate change worsens. Water will become increasingly scarce, adversely impacting every aspect of his life.

22. Xiuhtezcatl is also harmed by the adverse impacts to his air and water quality, and his health that result from the exploitation of fossil fuels in Colorado. Under authorizations by the Department of Energy, natural gas extracted through fracking in Colorado will be transported by pipeline to Oregon, liquefied at the Jordan Cove LNG Terminal in Coos Bay, and then shipped overseas for combustion. The LNG exports from Coos Bay, Oregon will harm Xiuhtezcatl because the export of natural gas enhances demand for natural gas extraction in Colorado and increases the atmospheric concentration of CO_2.

22-A. Xiuhtezcatl's individual injuries to his spiritual and cultural practices, his physical and mental health, his personal security and safety in his home and the forests and waters he relies upon for life sustenance and happiness are already occurring. Defendants' national energy system is a substantial cause of those actual injuries.

a. Defendants' national energy system worsens Xiuhtezcatl's individual injuries each year. Xiuhtezcatl is additionally injured by each passing year of losing the ability to prevent the worsening of his injuries. Xiuhtezcatl is also injured by each passing year of losing the ability to prevent the irreversibility and inevitability of a lifetime of worsening hardship to his spiritual and cultural practices, his physical and mental health, his personal security and safety in his home and the forests and waters he relies upon for life sustenance and happiness. The further

loss of the ability to protect his life, while suffering these harms, is a separate concrete psychological, emotional, and mental health injury to Xiuhtezcatl. Another separate injury is the deprivation of Xiuhtezcatl's ability to act in his own interest to preserve the window of opportunity to prevent irreversible and inevitable injury going forward and therefore protect his life, all the while suffering these ongoing harms each year from Defendants' national energy system, which they know is causing these injuries. The opportunity to prevent irreversible and inevitable injuries is still available now and is being progressively foreclosed by the ongoing national energy system. When the irreversibility of these harms becomes certain, redress will be forever foreclosed by this Court or the political majority through the ballot box. Thus, Xiuhtezcatl's injuries stem precisely from Defendants' belief, and resultant policies and practices, that the national energy system is constitutionally compliant.

b. Every attempt Xiuhtezcatl makes to safeguard his life, liberties, property, and equal protection of the law fails because Defendants view the national energy system as constitutionally compliant. As long as Defendants operate under the belief that the national energy system is constitutionally compliant, Defendants will continue to power it with fossil fuels at levels that are dangerous for Xiuhtezcatl and which foreclose his ability to obtain relief that will protect himself. The composition of the United States national energy system is the most important factor in the world as to whether Xiuhtezcatl can prevent his irreversible injury. If the national energy system remains predominantly fossil

fuel-based, Xiuhtezcatl will permanently lose his ability to obtain relief that will protect himself and his rights.

c. If this Court should issue a declaratory judgment to resolve this actual constitutional case and controversy between these young Plaintiffs and these government Defendants as to whether Defendants' national energy system has violated and continues to violate Plaintiffs' constitutional rights as described herein, the Court will have ordered a change in legal status that would have practical consequences. A declaratory judgment would significantly increase the likelihood that Xiuhtezcatl would obtain relief to safeguard his life, liberty, property, and equal protection of the law. If the Court declares the nation's energy system unconstitutional in its present form, Defendants will correct the unconstitutional policies and practices of the national energy system. The worsening of Xiuhtezcatl's injuries at the hands of his government will end, providing substantially meaningful partial redress of his injuries. The Court will thereby preserve Xiuhtezcatl's opportunity to obtain relief to safeguard his life, liberty, property, and equal protection of the law from irreversible and inevitable injury. Protecting the opportunity for freedom and happiness and safety and security, by eliminating a substantial federal government restraint on freedom and decreasing the substantial risk of irreversibility, is tremendously meaningful redress.

23. Plaintiff **Alexander Loznak** is a citizen of the U.S. and lives in the unincorporated area of Kellogg, Oregon. He is 18 years old and graduated from Roseburg High School in June 2015. Alex is experiencing harm caused by Defendants. For example, Alex is

gravely concerned about how his life and his family's farm will continue to be affected by climate change.

24. Alex lives on his family's 570-acre farm, the Martha A. Maupin Century Farm ("Maupin Century Farm"), located along the Umpqua River. His great, great, great, great grandmother, Martha Poindexter Maupin, founded the farm in 1868 (she was one of the first women in Oregon to own a ranch) after arriving in the area by way of the Oregon Trail. The Maupin Century Farm is Alex's intellectual and spiritual base and a foundational piece of his life and heritage, and his identity and wellbeing depend on its preservation and protection. However, the drought conditions, unusually hot temperatures, and climate-induced migration of forest species are harming and will increasingly harm Alex's use and enjoyment of the Maupin Century Farm.

25. Alex's ability to fish on local rivers is harmed by drought and hot temperatures. The Pacific Connector Natural Gas Pipeline, which would connect to the Jordan Cove LNG Terminal at Coos Bay, would be located only about 30 miles from the Maupin Century Farm, in a forest where Alex recreates. The Pacific Connector Natural Gas Pipeline would cross bodies of water at 400 different locations in Oregon, including two places on the South Umpqua River where Alex recreates. Alex has walked along the pipeline route and has seen the old growth trees that will be logged and the special rivers that will be impacted in order to deliver natural gas to what would be the largest, most-polluting facility and power plant in Oregon, solely built to liquefy natural gas for export and ultimate combustion.

26. The Maupin Century Farm is also an important source of revenue and food for Alex and his family. On the Farm, Alex and his family grow plum trees and hazelnut trees, raise chickens and grass-fed cows, and have a large garden growing many of the fruits and vegetables

that his family consumes. The record-setting heat waves and drought in Oregon adversely impact both Alex's life and the Farm, especially their hazelnut orchard. The heat waves and drought harm Alex's ability to work outside on the Farm during the summer months.

27. The Maupin Century Farm is home to many different species of wildlife, including deer, bears, mountain lions, and birds, which Alex enjoys seeing. Alex and his family hunt deer, elk, and wild turkeys to provide food. Each of these species of wildlife is adversely impacted by climate change caused by Defendants. Other food sources for Alex, including crab and seafood, are negatively impacted by ocean acidification, warming, and sea level rise caused by Defendants.

28. The health and bodily integrity of his family and their Farm, which they rely on for food and as a source of income—as well as for their personal wellbeing—increasingly are harmed by climate change caused by Defendants. The Maupin Century Farm has been passed from generation to generation in Alex's family, and in many ways Alex's future depends on that family farm. He would like to reside at, raise children on, and retire to the Maupin Century Farm, but he is concerned about how it will be further damaged by climate change caused by Defendants. Wildfires, more common and more destructive due to warmer summers and drought conditions, are increasingly common in Southern Oregon. The area where Alex lives is frequently smoky due to nearby wildfires during the warmer months. Additionally, Alex is allergic to pollen and suffers worse in unseasonably warm years. He also suffers from asthma, which is worse in the increasingly smoky summer months. Alex's allergies and asthma will worsen as climate change caused by Defendants worsens.

29. For recreation, Alex enjoys activities in the snow in Oregon and also hiking in Northern Washington and Glacier National Park, where he has seen the glaciers receding due to

climate change caused by Defendants. Alex plans to return to Montana, and he also plans to travel to Alaska, and his recreational and aesthetic interests are harmed as the glaciers continue to disappear before he can visit them.

30. Alex has taken individual action to try to protect the climate system by driving an efficient hybrid car, by starting a Climate Change Club at Roseburg High School with the goal of installing solar panels on the school's roof, by starting the League of Umpqua Climate Youth ("LUCY"), and by lobbying his state legislators to pass comprehensive climate legislation.

30-A. Alex's individual injuries to his health, his food sources, his home, his personal security and safety, his ability to work outside for part of the year, his family farm heritage, his freedom to live, travel, and recreate where he wants in the United States, are already occurring. Defendants' national energy system is a substantial cause of those actual injuries.

a. Defendants' national energy system worsens Alex's individual injuries each year. Alex is additionally injured by each passing year of losing the ability to prevent the worsening of his injuries. Alex is also injured by each passing year of losing the ability to prevent the irreversibility and inevitability of a lifetime of worsening hardship to his health, food sources, personal security and safety, ability to work, and protect his family farm. The further loss of the ability to protect his life, while suffering these harms, is a separate concrete psychological, emotional, and mental health injury to Alex. Another separate injury is the deprivation of Alex's ability to act in his own interest to preserve the window of opportunity to prevent irreversible and inevitable injury going forward and therefore protect his life, all the while suffering these ongoing harms each year from Defendants' national energy system, which they know is causing these injuries. The opportunity to

prevent irreversible and inevitable injuries is still available now and is being progressively foreclosed by the ongoing national energy system. When the irreversibility of these harms becomes certain, redress will be forever foreclosed by this Court or the political majority through the ballot box. Thus, Alex's injuries stem precisely from Defendants' belief, and resultant policies and practices, that the national energy system is constitutionally compliant.

b. Every attempt Alex makes to safeguard his life, liberties, property, and equal protection of the law fails because Defendants view the national energy system as constitutionally compliant. As long as Defendants operate under the belief that the national energy system is constitutionally compliant, Defendants will continue to power it with fossil fuels at levels that are dangerous for Alex and which foreclose his ability to obtain relief that will protect himself. The composition of the United States national energy system is the most important factor in the world as to whether Alex can prevent his irreversible injury. If the national energy system remains predominantly fossil fuel-based, Alex will permanently lose his ability to obtain relief that will protect himself and his rights.

c. If this Court should issue a declaratory judgment to resolve this actual constitutional case and controversy between these young Plaintiffs and these government Defendants as to whether Defendants' national energy system has violated and continues to violate Plaintiffs' constitutional rights as described herein, the Court will have ordered a change in legal status that would have practical consequences. A declaratory judgment would significantly increase the likelihood that Alex would obtain relief to safeguard his life, liberty, property, and

equal protection of the law. If the Court declares the nation's energy system unconstitutional in its present form, Defendants will correct the unconstitutional policies and practices of the national energy system. The worsening of Alex's injuries at the hands of his government will end, providing substantially meaningful partial redress of his injuries. The Court will thereby preserve Alex's opportunity to obtain relief to safeguard his life, liberty, property, and equal protection of the law from irreversible and inevitable injury. Protecting the opportunity for freedom and happiness and safety and security, by eliminating a substantial federal government restraint on freedom and decreasing the substantial risk of irreversibility, is tremendously meaningful redress.

31. Plaintiff **Jacob Lebel** is an 18-year-old citizen of the U.S. residing in Roseburg, Oregon. In 2000, Jacob and his family immigrated to Oregon from Quebec, Canada, attracted by the state's pristine landscape and temperate weather. Since then, Jacob's family has established Rose Hill Farms, a diverse, organically managed farm, as well as a thriving local medical practice at White Oak Medical Clinic. Jacob grew up working on Rose Hill Farms, where he currently spends most of his time. Jacob intends to continue his use and enjoyment of Rose Hill Farms for these purposes and for his vocational career in the future. Jacob derives educational, inspirational, spiritual, and other benefits from his work at the Farm. Jacob is harmed and will continue to be harmed by Defendants' actions described herein and the climate change impacts to the Farm, including the deterioration of the Farm environment, rising temperatures, and a dwindling water supply.

32. In the summer, Rose Hill Farms depends on home-dug ponds to irrigate a large garden and three greenhouses, as well as several orchards of more than four hundred fruit and

nut trees. The recent long, dry summers, droughts, and heat waves reduced, and are currently reducing, the supply of water in the ponds, just as the water needs of the crops and trees have increased. As climate impacts continue to grow in severity, so will this water shortage. Furthermore, experts predict that large destructive wildfires, aggravated by record-low snowpacks and consistently drier and hotter conditions, will become increasingly common in Oregon. A wildfire would destroy the fourteen years of work that have gone into making the Rose Hill Farms. In addition to the farm structures, orchards, greenhouses, and pastures at risk from a fire, approximately 70 percent of the 350 acres of land owned by Jacob's family is mixed conifer forest which they manage sustainably and which represents an enormous investment. Already, Jacob and his family are required to invest resources to install an irrigation system in order to contend with the increasing drought conditions as a result of climate destabilization caused by Defendants.

33. Throughout Jacob's life, wilderness and healthy natural environments have been essential parts of his spiritual and emotional wellbeing. Jacob frequently and regularly recreates in the natural areas of Oregon, through hiking, exploring, snowboarding, and rafting. Native ecosystems and animal species have always been the main source of inspiration for Jacob's writing, music, and poetry. Jacob also spends significant time fishing, gathering mussels, and crabbing as a source of both enjoyment and food for himself and his family. Jacob intends to continue all of these activities in the future. In 2014-2015, Jacob experienced drastic snow retreat on Crater Lake National Park and Mount Hood, as well as the nearby South Umpqua River drying up in some spots, adversely affecting his use and enjoyment of these areas. Low river flows and warm water temperatures all have contributed and contribute to losses of fish in the salmon runs in the rivers near Roseburg, on which Jacob relies for recreation and food.

Rising sea levels caused by Defendants threaten the natural areas of the Oregon coast used and enjoyed by Jacob. Ocean acidification caused by Defendants has already begun to adversely impact shellfish along the coast, and is projected to take its toll on crabs, mussels, and all shelled seafood. Jacob is adversely affected by these changes caused by Defendants' actions as described herein.

34. The Pacific Connector Natural Gas Pipeline, which would connect to the Jordan Cove LNG Terminal at Coos Bay, would run directly behind the Rose Hill Farms. The Pacific Connector Natural Gas Pipeline would adversely affect Jacob's aesthetic, inspirational, and spiritual enjoyment of the property. This pipeline also carries risks of dangerous leaks or explosions, which could trigger a wildfire in the hot summer months. The associated hundred-foot clear-cut area would affect the landscape integrity and biodiversity of Jacob's immediate surroundings, all of which adversely impact Jacob.

34-A. Jacob's individual injuries to his farm and livelihood, his food and water sources, his physical, spiritual and mental health, his personal security and safety in his home and the snow and waters he relies upon for life sustenance and happiness are already occurring. Defendants' national energy system is a substantial cause of those actual injuries.

a. Defendants' national energy system worsens Jacob's individual injuries each year. Jacob is additionally injured by each passing year of losing the ability to prevent the worsening of his injuries. Jacob is also injured by each passing year of losing the ability to prevent the irreversibility and inevitability of a lifetime of worsening hardship to his farm and livelihood, his food and water sources, his physical, spiritual and mental health, his personal security and safety in his home and the snow and waters he relies upon for life sustenance and happiness. The further loss

of the ability to protect his life, while suffering these harms, is a separate concrete psychological, emotional, and mental health injury to Jacob. Another separate injury is the deprivation of Jacob's ability to act in his own interest to preserve the window of opportunity to prevent irreversible and inevitable injury going forward and therefore protect his life, all the while suffering these ongoing harms each year from Defendants' national energy system, which they know is causing these injuries. The opportunity to prevent irreversible and inevitable injuries is still available now and is being progressively foreclosed by the ongoing national energy system. When the irreversibility of these harms becomes certain, redress will be forever foreclosed by this Court or the political majority through the ballot box. Thus, Jacob's injuries stem precisely from Defendants' belief, and resultant policies and practices, that the national energy system is constitutionally compliant.

b. Every attempt Jacob makes to safeguard his life, liberties, property, and equal protection of the law fails because Defendants view the national energy system as constitutionally compliant. As long as Defendants operate under the belief that the national energy system is constitutionally compliant, Defendants will continue to power it with fossil fuels at levels that are dangerous for Jacob and which foreclose his ability to obtain relief that will protect himself. The composition of the United States national energy system is the most important factor in the world as to whether Jacob can prevent his irreversible injury. If the national energy system remains predominantly fossil fuel-based, Jacob will permanently lose his ability to obtain relief that will protect himself and his rights.

c. If this Court should issue a declaratory judgment to resolve this actual constitutional case and controversy between these young Plaintiffs and these government Defendants as to whether Defendants' national energy system has violated and continues to violate Plaintiffs' constitutional rights as described herein, the Court will have ordered a change in legal status that would have practical consequences. A declaratory judgment would significantly increase the likelihood that Jacob would obtain relief to safeguard his life, liberty, property, and equal protection of the law. If the Court declares the nation's energy system unconstitutional in its present form, Defendants will correct the unconstitutional policies and practices of the national energy system. The worsening of Jacob's injuries at the hands of his government will end, providing substantially meaningful partial redress of his injuries. The Court will thereby preserve Jacob's opportunity to obtain relief to safeguard his life, liberty, property, and equal protection of the law from irreversible and inevitable injury. Protecting the opportunity for freedom and happiness and safety and security, by eliminating a substantial federal government restraint on freedom and decreasing the substantial risk of irreversibility, is tremendously meaningful redress.

35. Plaintiff **Zealand B.**, by and through his guardian and mother Kimberly Pash-Bell, is an 11-year-old citizen of the U.S. and a resident of Eugene, Oregon. Zealand has worked to increase community awareness about climate change caused by Defendants and has advocated before local and state governmental bodies for science-based government action on climate change. Zealand and his family minimize their impact on the environment and reduce their carbon footprint by biking, gardening, participating in community-supported agriculture, buying

locally-made products, and picking up litter in the places where they recreate. Zealand has experienced and will continue to experience harm from climate change caused by Defendants if immediate action is not taken to secure a stable climate system.

36. Zealand loves living in Oregon and hopes to stay in Oregon in the future. He enjoys skiing, biking, rock climbing, rafting, and camping in Oregon. Oregon's rivers are especially important to Zealand. While rafting along the rivers in Oregon, Zealand enjoys the solitude of the wilderness and the experience of seeing plants and animals in their natural habitat. Rafting trips with his family have been canceled or shortened due to the increased temperatures, drought, and reduced water levels. Zealand and his family twice experienced large forest fires while rafting on Oregon rivers.

37. The record-setting heat during the summer of 2015 adversely impacts Zealand and his enjoyment of outdoor activities by making bike-riding, playing soccer, and playing basketball difficult. Zealand suffers from allergies, which have increased in severity over the past few years, and caused him to decrease the amount of time that he spends outside in the spring and early summer. Heat waves and an increase in pollen counts will worsen with further climate change caused by Defendants and harm Zealand's recreational and health interests.

38. Warmer winters and decreased snowpack levels in Oregon have harmed, and will continue to harm, Zealand and his family. Zealand's mother usually works during the winter at the Willamette Pass ski resort, but that seasonal job was not available during the winter of 2014-2015 due to the lack of snow, resulting in lost income. The lack of snow also meant Zealand was unable to ski. Decreased snowpack levels in the future will also harm the availability of drinking water for Zealand, his family, and his community, as Eugene's only water source, the McKenzie River, is fed by melting snowpack.

39. Zealand and his family spend substantial time at the Oregon Coast. He enjoys playing in the dunes, camping, surfing, boogie boarding, and taking pictures of the ocean and surrounding areas. The impacts from warmer water temperatures, rising sea levels, and ocean acidification caused by Defendants will negatively impact Zealand's future ability to enjoy the same areas on the coast that he now loves and to eat the same seafood, which is an important part of his diet.

39-A. Zealand's individual injuries to his physical and mental health, his personal security and safety in his home and the snow, forests, and waters he relies upon for life sustenance and happiness are already occurring. Defendants' national energy system is a substantial cause of those actual injuries.

a. Defendants' national energy system worsens Zealand's individual injuries each year. Zealand is additionally injured by each passing year of losing the ability to prevent the worsening of his injuries. Zealand is also injured by each passing year of losing the ability to prevent the irreversibility and inevitability of a lifetime of worsening hardship to his physical and mental health, his personal security and safety in his home and the snow, forests, and waters he relies upon for life sustenance and happiness. The further loss of the ability to protect his life, while suffering these harms, is a separate concrete psychological, emotional, and mental health injury to Zealand. Another separate injury is the deprivation of Zealand's ability to act in his own interest to preserve the window of opportunity to prevent irreversible and inevitable injury going forward and therefore protect his life, all the while suffering these ongoing harms each year from Defendants' national energy system, which they know is causing these injuries. The opportunity to

prevent irreversible and inevitable injuries is still available now and is being progressively foreclosed by the ongoing national energy system. When the irreversibility of these harms becomes certain, redress will be forever foreclosed by this Court or the political majority through the ballot box. Thus, Zealand's injuries stem precisely from Defendants' belief, and resultant policies and practices, that the national energy system is constitutionally compliant.

b. Every attempt Zealand makes to safeguard his life, liberties, property, and equal protection of the law fails because Defendants view the national energy system as constitutionally compliant. As long as Defendants operate under the belief that the national energy system is constitutionally compliant, Defendants will continue to power it with fossil fuels at levels that are dangerous for Zealand and which foreclose his ability to obtain relief that will protect himself. The composition of the United States national energy system is the most important factor in the world as to whether Zealand can prevent his irreversible injury. If the national energy system remains predominantly fossil fuel-based, Zealand will permanently lose his ability to obtain relief that will protect himself and his rights.

c. If this Court should issue a declaratory judgment to resolve this actual constitutional case and controversy between these young Plaintiffs and these government Defendants as to whether Defendants' national energy system has violated and continues to violate Plaintiffs' constitutional rights as described herein, the Court will have ordered a change in legal status that would have practical consequences. A declaratory judgment would significantly increase the likelihood that Zealand would obtain relief to safeguard his life, liberty, property,

and equal protection of the law. If the Court declares the nation's energy system unconstitutional in its present form, Defendants will correct the unconstitutional policies and practices of the national energy system. The worsening of Zealand's injuries at the hands of his government will end, providing substantially meaningful partial redress of his injuries. The Court will thereby preserve Zealand's opportunity to obtain relief to safeguard his life, liberty, property, and equal protection of the law from irreversible and inevitable injury. Protecting the opportunity for freedom and happiness and safety and security, by eliminating a substantial federal government restraint on freedom and decreasing the substantial risk of irreversibility, is tremendously meaningful redress.

40. Plaintiff **Avery M.**, by and through her guardian and mother Holly McRae, is a 10-year-old citizen of the U.S. and a resident of Eugene, Oregon. Avery has worked to increase awareness in her community about impacts of climate change caused by Defendants and advocated for CO_2 reductions before her representatives at both the municipal and state levels. Avery and her family limit their carbon footprint as much as possible by recycling, biking, eating less meat and growing some of their own food, repairing, reusing, and buying second-hand goods, decreasing energy use at home, and minimizing their vehicle and air travel.

41. The impacts from climate change caused by Defendants are harming and will continue to harm Avery and her enjoyment of and interaction with nature and wildlife. Avery's favorite activity is swimming in natural bodies of water. Avery and her family enjoy boating, hiking, backpacking, camping, and watching salmon spawn throughout Oregon. In <u>2015</u>, Avery was not been able to participate in these recreational activities as frequently as past years due to warmer temperatures, drought, low water levels, forest fires, and algal blooms. The <u>2015</u>

summer heat has caused Avery to avoid outdoor activities to prevent becoming overheated. Avery also suffers from allergies, which will worsen with increased pollen count and a changing climate caused by Defendants. Avery enjoys taking vacations to Yellowstone with her family and has seen burned, beetle-killed forests on these trips. The increase of hungry bears in the area due to the decline in white bark pine trees forced her family to postpone Avery's first big backpacking trip in the area.

42. Climate change caused by Defendants has reduced snowpack levels in Oregon, negatively impacting Avery's enjoyment of winter activities and the future availability of drinking water for her and her family. Every winter, Avery takes a trip with her family to Clear Lake, where she enjoys snowshoeing and sledding. These winter activities were not possible from 2013-2015 due to lack of snow.

43. Avery enjoys eating seafood and going to the Oregon coast, where she wades in the water and explores tide pools. At the coast, Avery has noticed coastal erosion and her recreational experience is harmed by seeing dead wildlife from the coastal changes. Warmer water temperatures, sea level rise, and ocean acidification caused by Defendants will worsen and negatively impact Avery's enjoyment of the Oregon coast and the food she eats.

43-A. Avery's individual injuries to the waters of Oregon, her food sources, her physical and mental health, and the places in nature she relies upon for life, sustenance, and happiness, are already occurring. Defendants' national energy system is a substantial cause of those actual injuries.

a. Defendants' national energy system worsens Avery's individual injuries each year. Avery is additionally injured by each passing year of losing the ability to prevent the worsening of her injuries. Avery is also injured by each passing year

of losing the ability to prevent the irreversibility and inevitability of a lifetime of worsening hardship to her water and food sources, her physical and mental health, and the places in nature she relies upon for life, sustenance, and happiness. The further loss of the ability to protect her life, while suffering these harms, is a separate concrete psychological, emotional, and mental health injury to Avery. Another separate injury is the deprivation of Avery's ability to act in her own interest to preserve the window of opportunity to prevent irreversible and inevitable injury going forward and therefore protect her life, all the while suffering these ongoing harms each year from Defendants' national energy system, which they know is causing these injuries. The opportunity to prevent irreversible and inevitable injuries is still available now and is being progressively foreclosed by the ongoing national energy system. When the irreversibility of these harms becomes certain, redress will be forever foreclosed by this Court or the political majority through the ballot box. Thus, Avery's injuries stem precisely from Defendants' belief, and resultant policies and practices, that the national energy system is constitutionally compliant.

b. Every attempt Avery makes to safeguard her life, liberties, property, and equal protection of the law fails because Defendants view the national energy system as constitutionally compliant. As long as Defendants operate under the belief that the national energy system is constitutionally compliant, Defendants will continue to power it with fossil fuels at levels that are dangerous for Avery and which foreclose her ability to obtain relief that will protect herself. The composition of the United States national energy system is the most important factor in the world

as to whether Avery can prevent her irreversible injury. If the national energy system remains predominantly fossil fuel-based, Avery will permanently lose her ability to obtain relief that will protect herself and her rights.

c. If this Court should issue a declaratory judgment to resolve this actual constitutional case and controversy between these young Plaintiffs and these government Defendants as to whether Defendants' national energy system has violated and continues to violate Plaintiffs' constitutional rights as described herein, the Court will have ordered a change in legal status that would have practical consequences. A declaratory judgment would significantly increase the likelihood that Avery would obtain relief to safeguard her life, liberty, property, and equal protection of the law. If the Court declares the nation's energy system unconstitutional in its present form, Defendants will correct the unconstitutional policies and practices of the national energy system. The worsening of Avery's injuries at the hands of her government will end, providing substantially meaningful partial redress of her injuries. The Court will thereby preserve Avery's opportunity to obtain relief to safeguard her life, liberty, property, and equal protection of the law from irreversible and inevitable injury. Protecting the opportunity for freedom and happiness and safety and security, by eliminating a substantial federal government restraint on freedom and decreasing the substantial risk of irreversibility, is tremendously meaningful redress.

44. Plaintiff **Sahara V.**, by and through her guardian and mother Toña Aguilar, is an 11-year-old citizen of the U.S. and a resident of Eugene, Oregon. Sahara is experiencing harm as a result of Defendants' aggregate actions and omissions in causing climate change. Sahara has

been involved in both local and state initiatives to raise awareness about climate change and advocate for science-based CO_2 emission reductions. In order to reduce her impact on the environment, Sahara and her family bike, garden, recycle, and practice vegetarianism. Sahara spends time with her family recreating in Oregon's rivers, lakes, beaches, sand dunes, and forests. She enjoys swimming, biking, camping, and mushroom hunting. Sahara frequently visits her grandparents' home on the Mohawk River and has witnessed the water levels decrease dramatically.

45. Climate impacts caused by Defendants, such as increased temperatures and drought conditions, infringe upon Sahara's enjoyment and use of freshwater resources and will continue to do so in the future if immediate action is not taken to reduce CO_2 emissions. Sahara and her family take frequent trips to the Oregon coast to visit her grandparents, who own property in Yachats. On the Oregon coast, Sahara enjoys climbing rocks and sand dunes, swimming, and tidepooling to see marine life. Sahara's enjoyment of these activities is being increasingly harmed in the future by sea level rise, greater erosion, enhanced ocean acidification, and increased water temperatures.

46. Sahara has asthma, and the increased frequency of forest fires in Oregon, due to hotter and drier conditions, has triggered severe asthma attacks for Sahara. The smoke inhibits her ability to breath, causes her throat to close up, and necessitates the use of her inhaler. As a result of Defendants' actions in causing climate change, Sahara has become more susceptible to grass allergies, further aggravating her asthma. These health effects will worsen as climate change becomes more severe. Warmer winters and the lack of snow in Oregon have prevented Sahara's enjoyment of winter activities and will negatively impact her water supply in the future.

Sahara wants to stay in Oregon, yet she fears her children and grandchildren will be unable to experience and enjoy Oregon's natural resources and wildlife.

46-A. Sahara's individual injuries to her physical and mental health, water and food sources, her personal security and safety, her ability to seek sustenance and happiness in the natural places she enjoys, are already occurring. Defendants' national energy system is a substantial cause of those actual injuries.

a. Defendants' national energy system worsens Sahara's individual injuries each year. Sahara is additionally injured by each passing year of losing the ability to prevent the worsening of her injuries. Sahara is also injured by each passing year of losing the ability to prevent the irreversibility and inevitability of a lifetime of worsening hardship to physical and mental health, water and food sources, her personal security and safety, her ability to seek sustenance and happiness in the natural places she enjoys. The further loss of the ability to protect her life, while suffering these harms, is a separate concrete psychological, emotional, and mental health injury to Sahara. Another separate injury is the deprivation of Sahara's ability to act in her own interest to preserve the window of opportunity to prevent irreversible and inevitable injury going forward and therefore protect her life, all the while suffering these ongoing harms each year from Defendants' national energy system, which they know is causing these injuries. The opportunity to prevent irreversible and inevitable injuries is still available now and is being progressively foreclosed by the ongoing national energy system. When the irreversibility of these harms becomes certain, redress will be forever foreclosed by this Court or the political majority through the ballot box. Thus, Sahara's

injuries stem precisely from Defendants' belief, and resultant policies and practices, that the national energy system is constitutionally compliant.

b. Every attempt Sahara makes to safeguard her life, liberties, property, and equal protection of the law fails because Defendants view the national energy system as constitutionally compliant. As long as Defendants operate under the belief that the national energy system is constitutionally compliant, Defendants will continue to power it with fossil fuels at levels that are dangerous for Sahara and which foreclose her ability to obtain relief that will protect herself. The composition of the United States national energy system is the most important factor in the world as to whether Sahara can prevent her irreversible injury. If the national energy system remains predominantly fossil fuel-based, Sahara will permanently lose her ability to obtain relief that will protect herself and her rights.

c. If this Court should issue a declaratory judgment to resolve this actual constitutional case and controversy between these young Plaintiffs and these government Defendants as to whether Defendants' national energy system has violated and continues to violate Plaintiffs' constitutional rights as described herein, the Court will have ordered a change in legal status that would have practical consequences. A declaratory judgment would significantly increase the likelihood that Sahara would obtain relief to safeguard her life, liberty, property, and equal protection of the law. If the Court declares the nation's energy system unconstitutional in its present form, Defendants will correct the unconstitutional policies and practices of the national energy system. The worsening of Sahara's injuries at the hands of her government will end, providing substantially

meaningful partial redress of her injuries. The Court will thereby preserve Sahara's opportunity to obtain relief to safeguard her life, liberty, property, and equal protection of the law from irreversible and inevitable injury. Protecting the opportunity for freedom and happiness and safety and security, by eliminating a substantial federal government restraint on freedom and decreasing the substantial risk of irreversibility, is tremendously meaningful redress.

47. Plaintiff **Kiran Isaac Oommen** is an 18-year-old citizen of the U.S. and a resident of Eugene, Oregon. Kiran enjoys camping, hiking, kayaking, biking, and swimming in Oregon. In recent years, decreased water levels and rising temperatures have limited Kiran's enjoyment of both these activities and the special places in Oregon Kiran visits. Local Oregon produce and seafood are staples in Kiran's diet. Ocean acidification and the warmer water temperatures and lower water levels in rivers and streams have negatively impacted Kiran's ability to enjoy eating shellfish and salmon. Kiran enjoys cross-country skiing in the winter, but was not able to ski in 2015 due to the lack of snow in Oregon. Kiran enjoys visiting the Oregon coast to walk along the beach, swim, and go tidepooling. Impacts of climate change, such as sea level rise, will negatively impact Kiran's future ability to enjoy the Oregon coast.

48. Due to drastic seasonal variations, Kiran has endured increasingly severe grass and tree pollen allergies, making it difficult for them to enjoy outdoor activities. Kiran used to be able to regularly visit their friend's family farm in southern Oregon but the increased prevalence of forest fires due to dry conditions and high temperatures has impacted Kiran's ability to visit this farm, as the intensity of the smoke and ash have shortened their trips and inhibited their ability to breathe.

49. Kiran has family they visit in Olympia, Washington and near Miami, Florida, both areas scientists predict will be gravely impacted by sea level rise. When Kiran visited Florida in the past, they enjoyed seeing wildlife and experiencing the beauty of the Florida Keys, which is a place Kiran plans to visit again. Kiran would like to continue visiting their family in these coastal areas in the future, but the increasing severity of climate impacts, unless promptly abated, will prevent them from doing so – as large portions of these areas will be inundated by the rising seas.

49-A. Kiran's individual injuries to their water and food sources, their personal security and safety, their mental wellbeing, and their freedom to live, travel, and recreate safely, are already occurring. Defendants' national energy system is a substantial cause of those actual injuries.

a. Defendants' national energy system worsens Kiran's individual injuries each year. Kiran is additionally injured by each passing year of losing the ability to prevent the worsening of their injuries. Kiran is also injured by each passing year of losing the ability to prevent the irreversibility and inevitability of a lifetime of worsening hardship to their water and food sources, their personal security and safety, their mental wellbeing, and their freedom to live, travel, and recreate safely. The further loss of the ability to protect their life, while suffering these harms, is a separate concrete psychological, emotional, and mental health injury to Kiran. Another separate injury is the deprivation of Kiran's ability to act in their own interest to preserve the window of opportunity to prevent irreversible and inevitable injury going forward and therefore protect their life, all the while suffering these ongoing harms each year from Defendants' national energy

system, which they know is causing these injuries. The opportunity to prevent irreversible and inevitable injuries is still available now and is being progressively foreclosed by the ongoing national energy system. When the irreversibility of these harms becomes certain, redress will be forever foreclosed by this Court or the political majority through the ballot box. Thus, Kiran's injuries stem precisely from Defendants' belief, and resultant policies and practices, that the national energy system is constitutionally compliant.

b. Every attempt Kiran makes to safeguard their life, liberties, property, and equal protection of the law fails because Defendants view the national energy system as constitutionally compliant. As long as Defendants operate under the belief that the national energy system is constitutionally compliant, Defendants will continue to power it with fossil fuels at levels that are dangerous for Kiran and which foreclose their ability to obtain relief that will protect herself. The composition of the United States national energy system is the most important factor in the world as to whether Kiran can prevent their irreversible injury. If the national energy system remains predominantly fossil fuel-based, Kiran will permanently lose their ability to obtain relief that will protect themself and their rights.

c. If this Court should issue a declaratory judgment to resolve this actual constitutional case and controversy between these young Plaintiffs and these government Defendants as to whether Defendants' national energy system has violated and continues to violate Plaintiffs' constitutional rights as described herein, the Court will have ordered a change in legal status that would have practical consequences. A declaratory judgment would significantly increase the

likelihood that Kiran would obtain relief to safeguard their life, liberty, property, and equal protection of the law. If the Court declares the nation's energy system unconstitutional in its present form, Defendants will correct the unconstitutional policies and practices of the national energy system. The worsening of Kiran's injuries at the hands of their government will end, providing substantially meaningful partial redress of their injuries. The Court will thereby preserve Kiran's opportunity to obtain relief to safeguard their life, liberty, property, and equal protection of the law from irreversible and inevitable injury. Protecting the opportunity for freedom and happiness and safety and security, by eliminating a substantial federal government restraint on freedom and decreasing the substantial risk of irreversibility, is tremendously meaningful redress.

50. Plaintiff **Tia Marie Hatton** is a citizen of the U.S. and a resident of Bend, Oregon. She is 18 years old and will enter the University of Oregon in September 2015. For the past two years Tia has experienced pronounced climate change impacts in Bend and surrounding areas. Tia is an avid Nordic skier, and has skied competitively since middle school. During 2013-2015, her ability to ski was limited by the record low snowfall in the Bend area. Tia regularly skis at Virginia Meissner Sno-Park and Willamette Pass Resort. These areas were closed this past winter because of record low snowfall. In 2015, ski teams from across Oregon, including Tia's team, had to move their state competition to higher elevations at Mt. Bachelor where trails were limited and not well groomed. In the future, unless the severe impacts to our nation's climate system are immediately abated, she will not be able to ski at all, even at higher elevations.

51. For the 2015 summer, Oregon's Governor issued a drought declaration for Deschutes County, where Tia lives. Tia spends most of her time recreating outdoors, not only skiing, but cross-country running, rock climbing, hiking, camping, and kayaking. Warmer summer temperatures and forest fires in Deschutes National Forest south of Bend are preventing Tia from participating in these activities as often as she would like and once could. For the past several years there have been fires every summer in the forests surrounding Bend, and residents have had to evacuate. Tia is psychologically impacted by these events, as it is hard for her to watch the destruction of the wilderness she loves and its ecosystems. Tia and her family vacation around Oregon and have experienced coastal erosion in Seaside, Florence, and Newport. Tia has also experiences the climate impacts similar to those in the Bend area when she visits the Steens Mountain for running camp.

52. Tia works hard to protect the environment and create awareness about the impacts of climate change caused by Defendants. In high school she was a member of her school's Green Club, and spent time planning Earth Day activities to raise awareness and educate the student body. Tia tries to limit her transportation via cars and is participating in the Bend Energy Challenge, a nationwide energy-saving competition, to help her family save energy and make their home healthier.

52-A. Tia's individual injuries to her physical and mental wellbeing, her personal security and safety, and the snow that she depends on for her health and her pursuit of happiness are already occurring. Defendants' national energy system is a substantial cause of those actual injuries.

a. Defendants' national energy system worsens Tia's individual injuries each year. Tia is additionally injured by each passing year of losing the ability to prevent the

worsening of her injuries. Tia is also injured by each passing year of losing the ability to prevent the irreversibility and inevitability of a lifetime of worsening hardship to her physical and mental wellbeing, her personal security and safety, and the snow that she depends on for her health and her pursuit of happiness. The further loss of the ability to protect her life, while suffering these harms, is a separate concrete psychological, emotional, and mental health injury to Tia. Another separate injury is the deprivation of Tia's ability to act in her own interest to preserve the window of opportunity to prevent irreversible and inevitable injury going forward and therefore protect her life, all the while suffering these ongoing harms each year from Defendants' national energy system, which they know is causing these injuries. The opportunity to prevent irreversible and inevitable injuries is still available now and is being progressively foreclosed by the ongoing national energy system. When the irreversibility of these harms becomes certain, redress will be forever foreclosed by this Court or the political majority through the ballot box. Thus, Tia's injuries stem precisely from Defendants' belief, and resultant policies and practices, that the national energy system is constitutionally compliant.

b. Every attempt Tia makes to safeguard her life, liberties, property, and equal protection of the law fails because Defendants view the national energy system as constitutionally compliant. As long as Defendants operate under the belief that the national energy system is constitutionally compliant, Defendants will continue to power it with fossil fuels at levels that are dangerous for Tia and which foreclose her ability to obtain relief that will protect herself. The composition of the United

States national energy system is the most important factor in the world as to whether Tia can prevent her irreversible injury. If the national energy system remains predominantly fossil fuel-based, Tia will permanently lose her ability to obtain relief that will protect herself and her rights.

c. If this Court should issue a declaratory judgment to resolve this actual constitutional case and controversy between these young Plaintiffs and these government Defendants as to whether Defendants' national energy system has violated and continues to violate Plaintiffs' constitutional rights as described herein, the Court will have ordered a change in legal status that would have practical consequences. A declaratory judgment would significantly increase the likelihood that Tia would obtain relief to safeguard her life, liberty, property, and equal protection of the law. If the Court declares the nation's energy system unconstitutional in its present form, Defendants will correct the unconstitutional policies and practices of the national energy system. The worsening of Tia's injuries at the hands of her government will end, providing substantially meaningful partial redress of her injuries. The Court will thereby preserve Tia's opportunity to obtain relief to safeguard her life, liberty, property, and equal protection of the law from irreversible and inevitable injury. Protecting the opportunity for freedom and happiness and safety and security, by eliminating a substantial federal government restraint on freedom and decreasing the substantial risk of irreversibility, is tremendously meaningful redress.

53. Plaintiff **Isaac V.**, by and through his guardian and mother, Pamela Vergun, is a thirteen-year-old U.S. citizen and a resident of Beaverton, Oregon. Isaac is involved in climate

activism and he founded Plant for the Planet Academy in Oregon, along with his mom and sister. Isaac started a petition asking the city of Beaverton to adopt a resolution to lower the city's carbon emissions. At home, his family installed solar panels on their roof and they drive an electric vehicle.

54. Isaac and his family are experiencing the adverse impacts of climate change caused by Defendants. 2015 has been the hottest summer Isaac remembers, with temperatures at 100 degrees Fahrenheit in his hometown. The groundwater level in his backyard has dropped significantly, causing trees to die. Isaac enjoys recreating along the Spring Water Trail near Portland, Oregon and is harmed by the drought conditions, which have eliminated a substantial portion of the flow in Johnson Creek. In parts of southern and eastern Oregon, wildfires are tearing through forests where Isaac enjoys recreating, threatening the ecosystems he relies upon for his personal enjoyment.

55. In winter, Isaac recreates in the Oregon snow and thereby derives emotional, spiritual, and physical benefits. He intends to continue his use and enjoyment of the snow. The record-low snowfall across the state, caused by Defendants' actions and the climate change resulting from those actions, harms Isaac by reducing his opportunity to recreate in the snow.

56. Since he was very young, Isaac has had asthma. Isaac's asthma is worsening and will continue to worsen as air quality becomes more polluted from increased pollen counts and smoke from wildfires. Isaac enjoys athletic activities including hiking, soccer, and basketball. He intends to continue these activities in the future. Increasing temperatures caused by Defendants' actions will worsen his asthma, affect his athletic performance, and make him less likely to play sports.

56-A. Isaac's individual injuries to his lungs and his overall physical and mental health, as well as his personal security and safety, are already occurring. Defendants' national energy system is a substantial cause of those actual injuries.

a. Defendants' national energy system worsens Isaac's individual injuries each year. Isaac is additionally injured by each passing year of losing the ability to prevent the worsening of his injuries. Isaac is also injured by each passing year of losing the ability to prevent the irreversibility and inevitability of a lifetime of worsening hardship to his overall physical and mental health, as well as his personal security and safety. The further loss of the ability to protect his life, while suffering these harms, is a separate concrete psychological, emotional, and mental health injury to Isaac. Another separate injury is the deprivation of Isaac's ability to act in his own interest to preserve the window of opportunity to prevent irreversible and inevitable injury going forward and therefore protect his life, all the while suffering these ongoing harms each year from Defendants' national energy system, which they know is causing these injuries. The opportunity to prevent irreversible and inevitable injuries is still available now and is being progressively foreclosed by the ongoing national energy system. When the irreversibility of these harms becomes certain, redress will be forever foreclosed by this Court or the political majority through the ballot box. Thus, Isaac's injuries stem precisely from Defendants' belief, and resultant policies and practices, that the national energy system is constitutionally compliant.

b. Every attempt Isaac makes to safeguard his life, liberties, property, and equal protection of the law fails because Defendants view the national energy system as

constitutionally compliant. As long as Defendants operate under the belief that the national energy system is constitutionally compliant, Defendants will continue to power it with fossil fuels at levels that are dangerous for Isaac and which foreclose his ability to obtain relief that will protect himself. The composition of the United States national energy system is the most important factor in the world as to whether Isaac can prevent his irreversible injury. If the national energy system remains predominantly fossil fuel-based, Isaac will permanently lose his ability to obtain relief that will protect himself and his rights.

c. If this Court should issue a declaratory judgment to resolve this actual constitutional case and controversy between these young Plaintiffs and these government Defendants as to whether Defendants' national energy system has violated and continues to violate Plaintiffs' constitutional rights as described herein, the Court will have ordered a change in legal status that would have practical consequences. A declaratory judgment would significantly increase the likelihood that Isaac would obtain relief to safeguard his life, liberty, and equal protection of the law. If the Court declares the nation's energy system unconstitutional in its present form, Defendants will correct the unconstitutional policies and practices of the national energy system. The worsening of Isaac's injuries at the hands of his government will end, providing substantially meaningful partial redress of his injuries. The Court will thereby preserve Isaac's opportunity to obtain relief to safeguard his life, liberty, and equal protection of the law from irreversible and inevitable injury. Protecting the opportunity for freedom and happiness and safety and security, by eliminating a substantial

federal government restraint on freedom and decreasing the substantial risk of irreversibility, is tremendously meaningful redress.

57. Plaintiff **Miko V.**, by and through her guardian and mother, Pamela Vergun, is a 14-year-old citizen of the United States and a resident of Beaverton, Oregon. Miko is a climate activist. Along with her Mother and brother, Miko started the first Plant for the Planet Academy in Oregon to help plant 150 trees per person in the United States to combat deforestation. She is spreading awareness to other young people and working to educate adults about the climate crisis. At home, her family has solar panels on their roof and they use an electric hybrid vehicle to reduce their emissions when they drive. Miko is committed to living a low-carbon lifestyle.

58. Miko was born in the Marshall Islands, and her low-lying home island is threatened by sea level rise. She fears she will never be able to travel back to the Marshall Islands as she intends to because the islands will likely be underwater in the future. In the last couple of years, Miko has experienced record-breaking heat waves in Beaverton and Portland, Oregon. Miko recently visited Timothy Lake, 75 miles southeast of Beaverton, to swim and fish, but the water levels were lower than usual, negatively impacting her use and enjoyment of the area.

59. Seafood is an important part of Miko's diet. Ocean acidification and warming ocean, coastal, and river waters are negatively affecting the health of fish and sea life on which Miko depends.

59-A. Miko's individual injuries to her familial heritage and land, her food sources, her personal security and safety, her mental wellbeing, and her freedom to travel to and spend time in the Marshall Islands, are already occurring. Defendants' national energy system is a substantial cause of those actual injuries.

a. Defendants' national energy system worsens Miko's individual injuries each year. Miko is additionally injured by each passing year of losing the ability to prevent the worsening of her injuries. Miko is also injured by each passing year of losing the ability to prevent the irreversibility and inevitability of a lifetime of worsening hardship to her familial heritage and land, her food sources, her personal security and safety, her mental wellbeing, and her freedom to travel to and spend time in the Marshall Islands. The further loss of the ability to protect her life, while suffering these harms, is a separate concrete psychological, emotional, and mental health injury to Miko. Another separate injury is the deprivation of Miko's ability to act in her own interest to preserve the window of opportunity to prevent irreversible and inevitable injury going forward and therefore protect her life, all the while suffering these ongoing harms each year from Defendants' national energy system, which they know is causing these injuries. The opportunity to prevent irreversible and inevitable injuries is still available now and is being progressively foreclosed by the ongoing national energy system. When the irreversibility of these harms becomes certain, redress will be forever foreclosed by this Court or the political majority through the ballot box. Thus, Miko's injuries stem precisely from Defendants' belief, and resultant policies and practices, that the national energy system is constitutionally compliant.

b. Every attempt Miko makes to safeguard her life, liberties, property, and equal protection of the law fails because Defendants view the national energy system as constitutionally compliant. As long as Defendants operate under the belief that the national energy system is constitutionally compliant, Defendants will continue to

power it with fossil fuels at levels that are dangerous for Miko and which foreclose her ability to obtain relief that will protect herself. The composition of the United States national energy system is the most important factor in the world as to whether Miko can prevent her irreversible injury. If the national energy system remains predominantly fossil fuel-based, Miko will permanently lose her ability to obtain relief that will protect herself and her rights.

c. If this Court should issue a declaratory judgment to resolve this actual constitutional case and controversy between these young Plaintiffs and these government Defendants as to whether Defendants' national energy system has violated and continues to violate Plaintiffs' constitutional rights as described herein, the Court will have ordered a change in legal status that would have practical consequences. A declaratory judgment would significantly increase the likelihood that Miko would obtain relief to safeguard her life, liberty, property, and equal protection of the law. If the Court declares the nation's energy system unconstitutional in its present form, Defendants will correct the unconstitutional policies and practices of the national energy system. The worsening of Miko's injuries at the hands of her government will end, providing substantially meaningful partial redress of her injuries. The Court will thereby preserve Miko's opportunity to obtain relief to safeguard her life, liberty, property, and equal protection of the law from irreversible and inevitable injury. Protecting the opportunity for freedom and happiness and safety and security, by eliminating a substantial federal government restraint on freedom and decreasing the substantial risk of irreversibility, is tremendously meaningful redress.

60. Plaintiff **Hazel V.**, by and through her guardian and mother Margo Van Ummersen, is an 11-year-old citizen of the U.S. and a resident of Eugene, Oregon. Hazel has advocated in her community to raise awareness about climate change caused by Defendants and before her city leaders to ask for science-based reductions of CO_2 emissions. Hazel and her family reduce their carbon footprint by gardening, recycling, buying local products, biking, and walking.

61. Hazel enjoys swimming, canoeing, kayaking, camping, and hiking in Oregon. In recent years, she has been unable to fully enjoy these activities and special places she visits due to the increased temperatures, low water levels, and abnormal seasonal variations caused by the acts and omissions of Defendants. Hazel frequently visits the Oregon coast, where she enjoys bodysurfing, playing on the beach, tidepooling, harvesting seaweed, and hunting mushrooms. Increased surface and ocean temperatures, sea level rise, and ocean acidification caused by the acts of Defendants threaten Hazel's future ability to enjoy these activities, which are important aspects of her childhood. Salmon and seafood are important parts of Hazel's diet that will continue to be threatened due to increased water temperatures, drought, and ocean acidification caused by the acts of Defendants.

62. During the winter, Hazel enjoys skiing and sledding. However, due to declining snowpack and warmer winters, she has been unable to ski or sled. Decreased snowfall in the Cascades will have long-term adverse impacts on the water level in the McKenzie River, which provides drinking water to Hazel's hometown of Eugene. In June 2015, extreme heat caused by the acts of Defendants adversely impacted Hazel's health on a trip she took to Washington, D.C. During that trip, she suffered from two episodes of heat exhaustion.

62-A. Hazel's individual injuries to her personal security and safety, her mental wellbeing and physical health, and her freedom to live, recreate, and pursue happiness, are already occurring. Defendants' national energy system is a substantial cause of those actual injuries.

a. Defendants' national energy system worsens Hazel's individual injuries each year. Hazel is additionally injured by each passing year of losing the ability to prevent the worsening of her injuries. Hazel is also injured by each passing year of losing the ability to prevent the irreversibility and inevitability of a lifetime of worsening hardship to her personal security and safety, her mental wellbeing and physical health, and her freedom to live, recreate, and pursue happiness. The further loss of the ability to protect her life, while suffering these harms, is a separate concrete psychological, emotional, and mental health injury to Hazel. Another separate injury is the deprivation of Hazel's ability to act in her own interest to preserve the window of opportunity to prevent irreversible and inevitable injury going forward and therefore protect her life, all the while suffering these ongoing harms each year from Defendants' national energy system, which they know is causing these injuries. The opportunity to prevent irreversible and inevitable injuries is still available now and is being progressively foreclosed by the ongoing national energy system. When the irreversibility of these harms becomes certain, redress will be forever foreclosed by this Court or the political majority through the ballot box. Thus, Hazel's injuries stem precisely from Defendants' belief, and resultant policies and practices, that the national energy system is constitutionally compliant.

b. Every attempt Hazel makes to safeguard her life, liberties, property, and equal protection of the law fails because Defendants view the national energy system as constitutionally compliant. As long as Defendants operate under the belief that the national energy system is constitutionally compliant, Defendants will continue to power it with fossil fuels at levels that are dangerous for Hazel and which foreclose her ability to obtain relief that will protect herself. The composition of the United States national energy system is the most important factor in the world as to whether Hazel can prevent her irreversible injury. If the national energy system remains predominantly fossil fuel-based, Hazel will permanently lose her ability to obtain relief that will protect herself and her rights.

c. If this Court should issue a declaratory judgment to resolve this actual constitutional case and controversy between these young Plaintiffs and these government Defendants as to whether Defendants' national energy system has violated and continues to violate Plaintiffs' constitutional rights as described herein, the Court will have ordered a change in legal status that would have practical consequences. A declaratory judgment would significantly increase the likelihood that Hazel would obtain relief to safeguard her life, liberty, property, and equal protection of the law. If the Court declares the nation's energy system unconstitutional in its present form, Defendants will correct the unconstitutional policies and practices of the national energy system. The worsening of Hazel's injuries at the hands of her government will end, providing substantially meaningful partial redress of her injuries. The Court will thereby preserve Hazel's opportunity to obtain relief to safeguard her life, liberty, property, and equal

protection of the law from irreversible and inevitable injury. Protecting the opportunity for freedom and happiness and safety and security, by eliminating a substantial federal government restraint on freedom and decreasing the substantial risk of irreversibility, is tremendously meaningful redress.

63. Plaintiff **Sophie K.**, by and through her guardian and grandfather, Dr. James Hansen, is a 16-year-old citizen of the U.S., and a resident of Allentown, Pennsylvania. Through stories from her grandfather, Dr. James Hansen, Sophie has become passionate about climate science and feels a sense of urgency and responsibility to compel government action on climate change. Extreme weather events, including Hurricane Sandy, caused Sophie to miss school on many occasions; hailstorms have damaged her house; floodwaters often inundate roads by her house; and Sophie has even been forced to prepare for tornado warnings, which are very unusual for the area where she lives. Intense summer heat now diminishes Sophie's ability to participate in and enjoy outdoor activities, including track and tennis. Sophie would like to have the ability to one day live in coastal cities like New York or Los Angeles, but rising sea levels may inundate these coastal areas within Sophie's lifetime unless Defendants cease their actions that otherwise will soon ensure these catastrophic impacts. Sophie is distressed knowing the inundation of these, and other coastal hubs of our nation's economy and commerce, will have profoundly negative economic impacts on our nation and on her own life as she gets older, looks for work to support herself, and begins her professional career.

64. Climate change substantially caused by the acts of Defendants is harming, and will continue to harm, the ability of Sophie and her family to grow food in her garden as the population of bees and other pollinators decline. In <u>2015</u>, Sophie's health was adversely impacted for the first time by pollen allergies, a condition exacerbated by global and regional

warming. Extreme weather events, intense heat, and rising seas have had, and will increasingly have, a negative impact on Sophie. Sophie is deeply concerned about the future because she knows that climate change will not only harm her, but will also harm the entire fabric of human civilization and all living things on Earth that she cherishes and relies on for her life, liberties, and property.

64-A. Sophie's individual injuries to her food sources, her personal security and safety, her physical health and mental wellbeing, and her freedom to live in coastal areas and to pursue her happiness, are already occurring. Defendants' national energy system is a substantial cause of those actual injuries.

a. Defendants' national energy system worsens Sophie's individual injuries each year. Sophie is additionally injured by each passing year of losing the ability to prevent the worsening of her injuries. Sophie is also injured by each passing year of losing the ability to prevent the irreversibility and inevitability of a lifetime of worsening hardship to her food sources, her personal security and safety, her physical health and mental wellbeing, and her freedom to live in coastal areas and to pursue her happiness. The further loss of the ability to protect her life, while suffering these harms, is a separate concrete psychological, emotional, and mental health injury to Sophie. Another separate injury is the deprivation of Sophie's ability to act in her own interest to preserve the window of opportunity to prevent irreversible and inevitable injury going forward and therefore protect her life, all the while suffering these ongoing harms each year from Defendants' national energy system, which they know is causing these injuries. The opportunity to prevent irreversible and inevitable injuries is still available now and is being

progressively foreclosed by the ongoing national energy system. When the irreversibility of these harms becomes certain, redress will be forever foreclosed by this Court or the political majority through the ballot box. Thus, Sophie's injuries stem precisely from Defendants' belief, and resultant policies and practices, that the national energy system is constitutionally compliant.

b. Every attempt Sophie makes to safeguard her life, liberties, property, and equal protection of the law fails because Defendants view the national energy system as constitutionally compliant. As long as Defendants operate under the belief that the national energy system is constitutionally compliant, Defendants will continue to power it with fossil fuels at levels that are dangerous for Sophie and which foreclose her ability to obtain relief that will protect herself. The composition of the United States national energy system is the most important factor in the world as to whether Sophie can prevent her irreversible injury. If the national energy system remains predominantly fossil fuel-based, Sophie will permanently lose her ability to obtain relief that will protect herself and her rights.

c. If this Court should issue a declaratory judgment to resolve this actual constitutional case and controversy between these young Plaintiffs and these government Defendants as to whether Defendants' national energy system has violated and continues to violate Plaintiffs' constitutional rights as described herein, the Court will have ordered a change in legal status that would have practical consequences. A declaratory judgment would significantly increase the likelihood that Sophie would obtain relief to safeguard her life, liberty, property, and equal protection of the law. If the Court declares the nation's energy system

unconstitutional in its present form, Defendants will correct the unconstitutional policies and practices of the national energy system. The worsening of Sophie's injuries at the hands of her government will end, providing substantially meaningful partial redress of her injuries. The Court will thereby preserve Sophie's opportunity to obtain relief to safeguard her life, liberty, property, and equal protection of the law from irreversible and inevitable injury. Protecting the opportunity for freedom and happiness and safety and security, by eliminating a substantial federal government restraint on freedom and decreasing the substantial risk of irreversibility, is tremendously meaningful redress.

65. Plaintiff **Jaime B.**, by and through her guardian and mother Jamescita Peshlakai, is a 14-year-old citizen of the U.S. and a resident of Flagstaff, Arizona. Jaime is a member of the Navajo Nation. Jaime was born into the Bitter Water Clan, with maternal grandfathers of the Red House Clan and paternal grandfathers of the Towering House Clan. Jaime and her family are experiencing harm from climate change caused by the acts of Defendants and will experience even more severe climate impacts in the future. Since she was four years old, Jaime has been working to protect the earth. Beginning in elementary school, Jaime has written letters to President Obama about her concerns for the environment, asking him to protect the Arctic National Wildlife Refuge and ensure that oil spills do not continue to happen.

66. Jaime grew up in Cameron, Arizona, on the Navajo Nation Reservation. In <u>2011</u>, Jaime and her Mother had to move from Cameron to Flagstaff because of water scarcity. Jaime and her extended family on the Reservation remember times when there was enough water on the Reservation for agriculture and farm animals, but now the springs they once depended on year-round are drying up. Jaime and her Mother were not able to sustain living on the

Reservation because of the costs of hauling water into Cameron for themselves and their animals. Jaime is worried that her extended family, all of whom live on the Reservation, will also be displaced from their land, which will erode her culture and way of life. Participating in sacred Navajo ceremonies on the Reservation is an important part of Jaime's life, and climate impacts caused by the acts of Defendants are starting to harm the ability for Jamie and her tribe to participate in their traditional ceremonies.

67. Jaime now lives on property her Mother owns in the Kaibab National Forest. The forest is Jaime's favorite place to spend time. Jaime finds peace being outside in the forest surrounding her home, and she walks for 1-2 hours in the forest after school every day. Jaime's ability to spend time in the forest is going to be limited due to increasing climate change caused by the acts of Defendants. Large parts of the Kaibab National Forest have been destroyed due to pine beetle infestations and forest fires. In 2014, Jaime and her Mother were evacuated from their home for two days because of the Oak Creek Canyon fire north of their property. Winds brought smoke and ash into their neighborhood. Jaime is worried that the area surrounding their home is becoming unsafe due to an increase in drought conditions and forest fires caused by the acts of Defendants. Jaime and her Mother have seen climate change impact the vegetables they grow for food on their property in Flagstaff. Jaime's severe allergies have become increasingly worse over the last several years. She takes over-the-counter medication to combat her symptoms. With record-setting temperatures and a drought that has lasted several years, Jaime fears for her future and for the future of her family, their history, their traditions, and their way of life.

67-A. Jaime's individual injuries to her indigenous way of life, culture, and traditions, her family's property, her water and food sources, her personal security and safety, her physical

and mental health, and her freedom to pass to the next generation of Dine´ their heritage, are already occurring. Defendants' national energy system is a substantial cause of those actual injuries.

a. Defendants' national energy system worsens Jaime's individual injuries each year. Jaime is additionally injured by each passing year of losing the ability to prevent the worsening of her injuries. Jaime is also injured by each passing year of losing the ability to prevent the irreversibility and inevitability of a lifetime of worsening hardship to indigenous way of life, culture, and traditions, her family's property, her water and food sources, her personal security and safety, her physical and mental health, and her freedom to pass to the next generation of Dine´ their heritage. The further loss of the ability to protect her life, while suffering these harms, is a separate concrete psychological, emotional, and mental health injury to Jaime. Another separate injury is the deprivation of Jaime's ability to act in her own interest to preserve the window of opportunity to prevent irreversible and inevitable injury going forward and therefore protect her life, all the while suffering these ongoing harms each year from Defendants' national energy system, which they know is causing these injuries. The opportunity to prevent irreversible and inevitable injuries is still available now and is being progressively foreclosed by the ongoing national energy system. When the irreversibility of these harms becomes certain, redress will be forever foreclosed by this Court or the political majority through the ballot box. Thus, Jaime's injuries stem precisely from Defendants' belief, and resultant policies and practices, that the national energy system is constitutionally compliant.

b. Every attempt Jaime makes to safeguard her life, liberties, property, and equal protection of the law fails because Defendants view the national energy system as constitutionally compliant. As long as Defendants operate under the belief that the national energy system is constitutionally compliant, Defendants will continue to power it with fossil fuels at levels that are dangerous for Jaime and which foreclose her ability to obtain relief that will protect herself. The composition of the United States national energy system is the most important factor in the world as to whether Jaime can prevent her irreversible injury. If the national energy system remains predominantly fossil fuel-based, Jaime will permanently lose her ability to obtain relief that will protect herself and her rights.

c. If this Court should issue a declaratory judgment to resolve this actual constitutional case and controversy between these young Plaintiffs and these government Defendants as to whether Defendants' national energy system has violated and continues to violate Plaintiffs' constitutional rights as described herein, the Court will have ordered a change in legal status that would have practical consequences. A declaratory judgment would significantly increase the likelihood that Jaime would obtain relief to safeguard her life, liberty, property, and equal protection of the law. If the Court declares the nation's energy system unconstitutional in its present form, Defendants will correct the unconstitutional policies and practices of the national energy system. The worsening of Jaime's injuries at the hands of her government will end, providing substantially meaningful partial redress of her injuries. The Court will thereby preserve Jaime's opportunity to obtain relief to safeguard her life, liberty, property, and equal

protection of the law from irreversible and inevitable injury. Protecting the opportunity for freedom and happiness and safety and security, by eliminating a substantial federal government restraint on freedom and decreasing the substantial risk of irreversibility, is tremendously meaningful redress.

68. Plaintiff **Journey Z.**, by and through his guardian and mother Erika Schneider, is a 15-year-old citizen of the U.S. Journey is a Native American born in South Dakota and a federally enrolled member of the Yankton Sioux Tribe. In 2009, Journey and his family moved to the island of Kaua‘i, Hawai‘i. Journey attends a Hawaiian cultural immersion school, has adopted the Hawaiian culture as his own, and speaks the native Hawaiian language. Journey has deep cultural and spiritual connections with the Earth and all life. These connections depend on a stable climate system for survival, providing Journey with a fundamental sense of responsibility to protect the Earth for his generation and for future generations. Journey is a youth leader on the Rising Youth for a Sustainable Earth (“RYSE”) Youth Council and a youth ambassador for the Center for Native American Youth. Journey has advocated directly to President Obama’s administration and other federal government officials to secure government action to stabilize the climate system and protect his fundamental rights.

69. Journey participates in many culturally important activities, such as working in the taro fields, organic farming, playing Tahitian drum, fire dancing, and performing Halau Hula O Leilani. He also enjoys swimming, snorkeling, fishing, canoeing, stand-up paddle boarding, and walking and biking along the beach. His participation in and enjoyment of these activities has been and will continue to be negatively impacted by the impacts of climate change and ocean acidification caused by Defendants.

70. Journey's food security and his enjoyment of the biological diversity of the coral reefs are and will continue to be adversely impacted by ocean acidification and the climate change impacts of sea-level rise, increased sea surface temperature, alteration in ocean circulation, and increased storm intensity, all caused by the acts of Defendants. These problems are all deleterious to coral reefs in Hawaiʻi and their associated ecosystems and fisheries. Journey's health, personal safety, cultural practices, and recreational interests are adversely impacted by the climate impacts of rising sea levels and intense storms that increase coastal flooding and erosion in Hawaiʻi, damaging coastal ecosystems, infrastructure, and agriculture, on which Journey relies. Watching beaches erode away and disappear has emotionally harmed Journey. Journey performs Halau Hula O Leilani at the hotels along the beaches and will not be able to do so in the future with continued sea level rise. The rock wall at Journey's favorite swimming beach eroded and fell into the ocean, and additional erosion will make it unsafe for Journey to swim there in the future. Decreased rainfall on Kauaʻi and the resulting lower river water levels, combined with saltwater inundation from sea level rise, have caused serious water quality problems, high bacteria levels, and increased shark activities that threaten Journey's health and safety, preventing his use and enjoyment of rivers he frequently enjoyed. Declining freshwater availability also threatens Journey's future access to drinking water and ability to stay on the island. Drought conditions on part of Kaua'i and saltwater inundation negatively impact the soil and the agricultural productivity of the farms and taro patches where Journey works. While total rainfall has decreased, rain intensity has increased. In <u>2012</u>, this increased rain intensity threatened Journey's personal safety when he and his family were displaced by widespread flooding and evacuated to a Red Cross shelter.

70-A. Journey's individual injuries to his physical and mental health, personal security and safety, cultural practices, food and freshwater sources, and the coral reefs and ocean life he depends on for sustenance and happiness are already occurring. Defendants' national energy system is a substantial cause of those actual injuries.

a. Defendants' national energy system worsens Journey's individual injuries each year. Journey is additionally injured by each passing year of losing the ability to prevent the worsening of his injuries. Journey is also injured by each passing year of losing the ability to prevent the irreversibility and inevitability of a lifetime of worsening hardship to his physical and mental health, personal security and safety, cultural practices, food and freshwater sources, and the coral reefs and ocean life he depends on for sustenance and happiness. The further loss of the ability to protect his life, while suffering these harms, is a separate concrete psychological, emotional, and mental health injury to Journey. Another separate injury is the deprivation of Journey's ability to act in his own interest to preserve the window of opportunity to prevent irreversible and inevitable injury going forward and therefore protect his life, all the while suffering these ongoing harms each year from Defendants' national energy system, which they know is causing these injuries. The opportunity to prevent irreversible and inevitable injuries is still available now and is being progressively foreclosed by the ongoing national energy system. When the irreversibility of these harms becomes certain, redress will be forever foreclosed by this Court or the political majority through the ballot box. Thus, Journey's injuries stem precisely from Defendants' belief, and

resultant policies and practices, that the national energy system is constitutionally compliant.

b. Every attempt Journey makes to safeguard his life, liberties, property, and equal protection of the law fails because Defendants view the national energy system as constitutionally compliant. As long as Defendants operate under the belief that the national energy system is constitutionally compliant, Defendants will continue to power it with fossil fuels at levels that are dangerous for Journey and which foreclose his ability to obtain relief that will protect himself. The composition of the United States national energy system is the most important factor in the world as to whether Journey can prevent his irreversible injury. If the national energy system remains predominantly fossil fuel-based, Journey will permanently lose his ability to obtain relief that will protect himself and his rights.

c. If this Court should issue a declaratory judgment to resolve this actual constitutional case and controversy between these young Plaintiffs and these government Defendants as to whether Defendants' national energy system has violated and continues to violate Plaintiffs' constitutional rights as described herein, the Court will have ordered a change in legal status that would have practical consequences. A declaratory judgment would significantly increase the likelihood that Journey would obtain relief to safeguard his life, liberty, property, and equal protection of the law. If the Court declares the nation's energy system unconstitutional in its present form, Defendants will correct the unconstitutional policies and practices of the national energy system. The worsening of Journey's injuries at the hands of his government will end, providing substantially

meaningful partial redress of his injuries. The Court will thereby preserve Journey's opportunity to obtain relief to safeguard his life, liberty, property, and equal protection of the law from irreversible and inevitable injury. Protecting the opportunity for freedom and happiness and safety and security, by eliminating a substantial federal government restraint on freedom and decreasing the substantial risk of irreversibility, is tremendously meaningful redress.

71. Plaintiff **Vic B.**, by and through his guardian and mother Daisy Calderon, is a 16-year-old citizen of the U.S. and a resident of White Plains, New York. In September 2015, Vic will be a junior in high school at Notre Dame School of Manhattan in New York City. Since 2013, Vic has been active in the climate movement, educating people about climate change and working to mitigate it. Vic was a fellow with the Alliance for Climate Education and continues to advocate for education and action on climate change in New York.

72. Vic has become emotionally distressed by the increase in superstorms in the Northeast. Vic was harmed by Hurricane Sandy when he and his family lost power to their home, his school shut down, and his forms of public transportation were not operating. Vic is also harmed by the increasing sweltering summer temperatures, which limit the time he spends outdoors in New York. In recent years, his pollen allergies have become worse, making it even more difficult to enjoy being outside. Vic lives on low-lying land, which is threatened by rising sea levels and more frequent storm surges.

72-A. Vic is Honduran-American and belongs to the Afro-Indigenous Garifuna community that settled on the northern coast of Honduras hundreds of years ago and his and his family's traditional heritage, way of life, food sources, land, and home are critically endangered by sea level rise. Vic's individual injuries to his Garifuna heritage, his physical and mental

health, his personal security and safety, and his family's property are already occurring. Defendants' national energy system is a substantial cause of those actual injuries.

a. Defendants' national energy system worsens Vic's individual injuries each year. Vic is additionally injured by each passing year of losing the ability to prevent the worsening of his injuries. Vic is also injured by each passing year of losing the ability to prevent the irreversibility and inevitability of a lifetime of worsening hardship to his Garifuna heritage, his physical and mental health, his personal security and safety, and his family's property. The further loss of the ability to protect his life, while suffering these harms, is a separate concrete psychological, emotional, and mental health injury to Vic. Another separate injury is the deprivation of Vic's ability to act in his own interest to preserve the window of opportunity to prevent irreversible and inevitable injury going forward and therefore protect his life, all the while suffering these ongoing harms each year from Defendants' national energy system, which they know is causing these injuries. The opportunity to prevent irreversible and inevitable injuries is still available now and is being progressively foreclosed by the ongoing national energy system. When the irreversibility of these harms becomes certain, redress will be forever foreclosed by this Court or the political majority through the ballot box. Thus, Vic's injuries stem precisely from Defendants' belief, and resultant policies and practices, that the national energy system is constitutionally compliant.

b. Every attempt Vic makes to safeguard his life, liberties, property, and equal protection of the law fails because Defendants view the national energy system as

constitutionally compliant. As long as Defendants operate under the belief that the national energy system is constitutionally compliant, Defendants will continue to power it with fossil fuels at levels that are dangerous for Vic and which foreclose his ability to obtain relief that will protect himself. The composition of the United States national energy system is the most important factor in the world as to whether Vic can prevent his irreversible injury. If the national energy system remains predominantly fossil fuel-based, Vic will permanently lose his ability to obtain relief that will protect himself and his rights.

c. If this Court should issue a declaratory judgment to resolve this actual constitutional case and controversy between these young Plaintiffs and these government Defendants as to whether Defendants' national energy system has violated and continues to violate Plaintiffs' constitutional rights as described herein, the Court will have ordered a change in legal status that would have practical consequences. A declaratory judgment would significantly increase the likelihood that Vic would obtain relief to safeguard his life, liberty, property, and equal protection of the law. If the Court declares the nation's energy system unconstitutional in its present form, Defendants will correct the unconstitutional policies and practices of the national energy system. The worsening of Vic's injuries at the hands of his government will end, providing substantially meaningful partial redress of his injuries. The Court will thereby preserve Vic's opportunity to obtain relief to safeguard his life, liberty, property, and equal protection of the law from irreversible and inevitable injury. Protecting the opportunity for freedom and happiness and safety and security, by eliminating a

substantial federal government restraint on freedom and decreasing the substantial risk of irreversibility, is tremendously meaningful redress.

73. Plaintiff **Nathaniel B.**, by and through his guardian and mother Sharon Baring, is a 15-year-old citizen of the U.S. and a resident of Fairbanks, Alaska. Nathaniel and his family are already witnessing the impacts of climate change and he is psychologically harmed knowing of the inevitable and increasingly severe climate impacts he will experience in the future.

74. Nathaniel is an avid Nordic skier who also enjoys downhill skiing. Nathaniel has been harmed by the reduced snowfall during the past few winters. Snow that typically comes in August is coming as late as November. In 2014-2015, Anchorage received its lowest seasonal snowfall to date. Nathaniel is experiencing more ice storms in Fairbanks. Last year the city declared a state of disaster after a severe ice storm created widespread power outages. Nathaniel and his family suffered without power for nearly a week in temperatures of 18 degrees Fahrenheit.

75. This summer, Alaska experienced over 300 wildfires across the state, all occurring at once. Wildfires have become a common occurrence every summer in Alaska. During the summer of 2015, Fairbanks was surrounded by numerous wildfires and air quality rivaled that of some of the world's smoggiest cities. As an asthma and allergy sufferer, the hot dry wildfire season makes it hard for Nathaniel to breathe outside and participate in cross-country running, one of his favorite sports. Nathaniel is distraught knowing that changing temperatures caused by Defendants will affect his way of life and the animals and ecosystems that surround him and on which he relies for recreation and food. His family raises chickens on their property and they hunt for moose and grouse for food. These animals are harmed by the extreme climate changes happening in Alaska caused by Defendants. Nathaniel has also noticed

a sharp decline of salmon, especially king salmon, which is important for his diet. This summer Alaska had a very small king salmon run on the Yukon River. Nathaniel and his family take fishing trips and he has experienced firsthand the decline in salmon runs. Nathaniel enjoys visiting Alaska's glaciers and intends to continue to do so. However, the glaciers Nathaniel visits are significantly receding, including the Mendenhall Glacier in Juneau, which has retreated over 1.5 miles.

76. Nathaniel is working hard to take actions to reverse and mitigate the effects of climate change through his membership in Alaska Youth for Environmental Action and his work with Citizens Climate Lobby and his church. At home, Nathaniel and his family try to ride bikes as much as possible. Nathaniel participates in the "dime a gallon" program at church, where members contribute a certain pre-arranged amount for every gallon of gas they use for transportation, which is then used to install insulation in their buildings, and other greening projects, such as solar panels.

76-A. Nathaniel's individual injuries to his physical and mental health, his food sources, his personal security and safety in his home, and the snow and winter conditions that he relies upon for life, sustenance, and happiness are already occurring. Defendants' national energy system is a substantial cause of those actual injuries.

a. Defendants' national energy system worsens Nathaniel's individual injuries each year. Nathaniel is additionally injured by each passing year of losing the ability to prevent the worsening of his injuries. Nathaniel is also injured by each passing year of losing the ability to prevent the irreversibility and inevitability of a lifetime of worsening hardship to his physical and mental health, his food sources, his personal security and safety in his home, and the snow and winter conditions

that he relies upon for life, sustenance, and happiness. The further loss of the ability to protect his life, while suffering these harms, is a separate concrete psychological, emotional, and mental health injury to Nathaniel. Another separate injury is the deprivation of Nathaniel's ability to act in his own interest to preserve the window of opportunity to prevent irreversible and inevitable injury going forward and therefore protect his life, all the while suffering these ongoing harms each year from Defendants' national energy system, which they know is causing these injuries. The opportunity to prevent irreversible and inevitable injuries is still available now and is being progressively foreclosed by the ongoing national energy system. When the irreversibility of these harms becomes certain, redress will be forever foreclosed by this Court or the political majority through the ballot box. Thus, Nathaniel's injuries stem precisely from Defendants' belief, and resultant policies and practices, that the national energy system is constitutionally compliant.

b. Every attempt Nathaniel makes to safeguard his life, liberties, property, and equal protection of the law fails because Defendants view the national energy system as constitutionally compliant. As long as Defendants operate under the belief that the national energy system is constitutionally compliant, Defendants will continue to power it with fossil fuels at levels that are dangerous for Nathaniel and which foreclose his ability to obtain relief that will protect himself. The composition of the United States national energy system is the most important factor in the world as to whether Nathaniel can prevent his irreversible injury. If the national energy

system remains predominantly fossil fuel-based, Nathaniel will permanently lose his ability to obtain relief that will protect himself and his rights.

c. If this Court should issue a declaratory judgment to resolve this actual constitutional case and controversy between these young Plaintiffs and these government Defendants as to whether Defendants' national energy system has violated and continues to violate Plaintiffs' constitutional rights as described herein, the Court will have ordered a change in legal status that would have practical consequences. A declaratory judgment would significantly increase the likelihood that Nathaniel would obtain relief to safeguard his life, liberty, property, and equal protection of the law. If the Court declares the nation's energy system unconstitutional in its present form, Defendants will correct the unconstitutional policies and practices of the national energy system. The worsening of Nathaniel's injuries at the hands of his government will end, providing substantially meaningful partial redress of his injuries. The Court will thereby preserve Nathaniel's opportunity to obtain relief to safeguard his life, liberty, property, and equal protection of the law from irreversible and inevitable injury. Protecting the opportunity for freedom and happiness and safety and security, by eliminating a substantial federal government restraint on freedom and decreasing the substantial risk of irreversibility, is tremendously meaningful redress.

77. Plaintiff **Aji P.**, by and through his guardian and mother Helaina Piper, is a 15-year-old citizen of the U.S. and a resident of West Seattle, Washington. Aji is experiencing the impacts of climate change caused by Defendants, and has been harmed by the increasing severity

of such impacts. In 2014, the State of Washington had the worst wildfire in the state's recorded history, the Carlton Complex fire. Aji and his family were impacted by that wildfire while on a trip through the Cascade Mountains when they were forced to breathe the smoke in the air. During the summer of 2015, Aji has struggled to participate in his regular summer outdoor activities because of temperatures climbing above 90 degrees Fahrenheit for extended periods, which is highly unusual for temperate Seattle.

78. Aji has also experienced the negative effects of climate change on Puget Sound and the freshwater systems and fish. The decreasing water quality in Puget Sound is causing dead zones to occur and ocean acidification is killing fish and shellfish. Aji recreates in these areas and enjoys seeing marine life. The impacts to shellfish and the diminishing numbers of starfish harm Aji's recreational and aesthetic interests. Aji has also been unable to touch or eat shellfish in Puget Sound due to toxicity levels. Aji is distraught by seeing the ecosystems surrounding his home harmed by climate change and ocean acidification caused by Defendants.

79. The impacts of climate change in other places in the western United States are also affecting Aji. On a trip to Montana with his grandparents, Aji experienced dead forests killed by pine bark beetles. Although Aji's mother is from Albuquerque, New Mexico, and they have family there, Aji and his family will not move back to New Mexico because of water shortage issues and the declining aquifer.

80. Aji advocates for actions to reverse and mitigate the effects of climate change caused by Defendants. He is a member of Plant for the Planet Leadership Corps, in which he plants trees, helps restore local forests, and speaks to the public about climate change impacts. He is also a member of Rising Youth for a Sustainable Earth. Aji is a vegetarian and he and his

family try to limit the time they spend driving as much as possible, opting to walk, bike, or take public transportation.

80-A. Aji's individual injuries to his physical and mental health, his personal security and safety, and the natural areas he relies upon for life, sustenance, and happiness are already occurring. Defendants' national energy system is a substantial cause of those actual injuries.

a. Defendants' national energy system worsens Aji's individual injuries each year. Aji is additionally injured by each passing year of losing the ability to prevent the worsening of his injuries. Aji is also injured by each passing year of losing the ability to prevent the irreversibility and inevitability of a lifetime of worsening hardship to his physical and mental health, his personal security and safety, and the natural areas he relies upon for life, sustenance, and happiness. The further loss of the ability to protect his life, while suffering these harms, is a separate concrete psychological, emotional, and mental health injury to Aji. Another separate injury is the deprivation of Aji's ability to act in his own interest to preserve the window of opportunity to prevent irreversible and inevitable injury going forward and therefore protect his life, all the while suffering these ongoing harms each year from Defendants' national energy system, which they know is causing these injuries. The opportunity to prevent irreversible and inevitable injuries is still available now and is being progressively foreclosed by the ongoing national energy system. When the irreversibility of these harms becomes certain, redress will be forever foreclosed by this Court or the political majority through the ballot box. Thus, Aji's injuries stem precisely from Defendants' belief, and

resultant policies and practices, that the national energy system is constitutionally compliant.

b. Every attempt Aji makes to safeguard his life, liberties, property, and equal protection of the law fails because Defendants view the national energy system as constitutionally compliant. As long as Defendants operate under the belief that the national energy system is constitutionally compliant, Defendants will continue to power it with fossil fuels at levels that are dangerous for Aji and which foreclose his ability to obtain relief that will protect himself. The composition of the United States national energy system is the most important factor in the world as to whether Aji can prevent his irreversible injury. If the national energy system remains predominantly fossil fuel-based, Aji will permanently lose his ability to obtain relief that will protect himself and his rights.

c. If this Court should issue a declaratory judgment to resolve this actual constitutional case and controversy between these young Plaintiffs and these government Defendants as to whether Defendants' national energy system has violated and continues to violate Plaintiffs' constitutional rights as described herein, the Court will have ordered a change in legal status that would have practical consequences. A declaratory judgment would significantly increase the likelihood that Aji would obtain relief to safeguard his life, liberty, and equal protection of the law. If the Court declares the nation's energy system unconstitutional in its present form, Defendants will correct the unconstitutional policies and practices of the national energy system. The worsening of Aji's injuries at the hands of his government will end, providing substantially

meaningful partial redress of his injuries. The Court will thereby preserve Aji's opportunity to obtain relief to safeguard his life, liberty, and equal protection of the law from irreversible and inevitable injury. Protecting the opportunity for freedom and happiness and safety and security, by eliminating a substantial federal government restraint on freedom and decreasing the substantial risk of irreversibility, is tremendously meaningful redress.

81. Plaintiff **Levi D.**, by and through his guardian and mother Leigh-Ann Draheim, is a citizen of the U.S. and a resident of Indialantic, Florida. Levi is 8-years-old and he is experiencing the impacts of climate change and working to take action and spread awareness about protecting the climate system.

82. Levi lives with his Mother and maternal grandparents in Indialantic, which is situated on a barrier island that separates the Indian River Lagoon from the Atlantic Ocean. The barrier island consists of primarily unconsolidated sand that sits on top of porous limestone bedrock. During the summer of 2015, Levi experienced a lack of rainfall that the island usually receives in the afternoons. Temperatures have been abnormally hot, making it harder than normal for Levi and his family to grow vegetables and herbs.

83. The beaches on the island are Levi's backyard. During the summer months he spends time at the beach five days a week. In the last couple of years, Levi has noticed a Sargassum seaweed invasion, with seaweed covering the beaches along the island. Levi is having a hard time enjoying beach activities because the rotting seaweed smells like sulfur. Levi has also seen climate impacts affect ecosystems at the beach, and has specifically experienced fewer sea turtles in the area. Levi can no longer swim in the Indian River Lagoon because of increasing flesh-eating bacteria and dead fish. Levi and his family are able to smell the dead fish

in their community. He is also now limited by where he can swim in the Atlantic Ocean, due to an increase in flesh-eating bacteria.

84. Levi and his family regularly visit the City of Satellite Beach. In 2009, Satellite Beach, an 8-minute drive from Levi's house, authorized a project to assess rising sea levels and work to mitigate impacts. In July 2010, the Sea Level Rise Subcommittee of Satellite Beach provided the results of the study: the City needs to plan for sea level rise. The island's real estate prices are declining, and Levi's family knows the property they own will decrease in value, and could eventually be lost completely, due to sea level rise caused by climate change and melting ice.

85. In the last two years, Levi's severe allergies have made it harder for him to spend time outdoors. Experiencing nature and wilderness in healthy conditions is important for Levi's emotional wellbeing, and his fears for the future of the beaches and springs in Florida and the wildlife that inhabit them are causing adverse psychological impacts to Levi. Levi works hard to keep the environment healthy on the coast by cleaning up the beaches and maintaining the dunes; at church by teaching his friends about how they can help the environment; and at home by conserving water by taking short timed showers, eating a vegetarian diet, and recycling.

85-A. Levi's individual injuries to his physical and mental health, his personal security and safety in his home, his family's property, and the waters and beaches and wildlife he relies upon for life, sustenance, and happiness are already occurring. Defendants' national energy system is a substantial cause of those actual injuries.

a. Defendants' national energy system worsens Levi's individual injuries each year. Levi is additionally injured by each passing year of losing the ability to prevent the worsening of his injuries. Levi is also injured by each passing year of losing

the ability to prevent the irreversibility and inevitability of a lifetime of worsening hardship to his physical and mental health, his personal security and safety in his home, his family's property, and the waters and beaches and wildlife he relies upon for life, sustenance, and happiness. The further loss of the ability to protect his life, while suffering these harms, is a separate concrete psychological, emotional, and mental health injury to Levi. Another separate injury is the deprivation of Levi's ability to act in his own interest to preserve the window of opportunity to prevent irreversible and inevitable injury going forward and therefore protect his life, all the while suffering these ongoing harms each year from Defendants' national energy system, which they know is causing these injuries. The opportunity to prevent irreversible and inevitable injuries is still available now and is being progressively foreclosed by the ongoing national energy system. When the irreversibility of these harms becomes certain, redress will be forever foreclosed by this Court or the political majority through the ballot box. Thus, Levi's injuries stem precisely from Defendants' belief, and resultant policies and practices, that the national energy system is constitutionally compliant.

b. Every attempt Levi makes to safeguard his life, liberties, property, and equal protection of the law fails because Defendants view the national energy system as constitutionally compliant. As long as Defendants operate under the belief that the national energy system is constitutionally compliant, Defendants will continue to power it with fossil fuels at levels that are dangerous for Levi and which foreclose his ability to obtain relief that will protect himself. The composition of the United

States national energy system is the most important factor in the world as to whether Levi can prevent his irreversible injury. If the national energy system remains predominantly fossil fuel-based, Levi will permanently lose his ability to obtain relief that will protect himself and his rights.

c. If this Court should issue a declaratory judgment to resolve this actual constitutional case and controversy between these young Plaintiffs and these government Defendants as to whether Defendants' national energy system has violated and continues to violate Plaintiffs' constitutional rights as described herein, the Court will have ordered a change in legal status that would have practical consequences. A declaratory judgment would significantly increase the likelihood that Levi would obtain relief to safeguard his life, liberty, property, and equal protection of the law. If the Court declares the nation's energy system unconstitutional in its present form, Defendants will correct the unconstitutional policies and practices of the national energy system. The worsening of Levi's injuries at the hands of his government will end, providing substantially meaningful partial redress of his injuries. The Court will thereby preserve Levi's opportunity to obtain relief to safeguard his life, liberty, property, and equal protection of the law from irreversible and inevitable injury. Protecting the opportunity for freedom and happiness and safety and security, by eliminating a substantial federal government restraint on freedom and decreasing the substantial risk of irreversibility, is tremendously meaningful redress.

86. Plaintiff **Jayden F.**, by and through her mother and guardian Cherri Foytlin, is a 12-year-old citizen of the U.S. and a resident of Rayne, Louisiana. In <u>2005</u>, Jayden moved to

Louisiana Since then, she has lived through three hurricanes and many more tropical storms. Jayden has suffered harm and will continue to suffer harm to her and her family's personal safety, bodily integrity, property, economic stability, food security, and recreational interests from rising sea levels, increased frequency and severity of hurricanes with ensuing storm surges, flooding, and high winds, all associated with or exacerbated by climate change caused by Defendants. Jayden is also directly harmed by Defendants' support and promotion of fossil fuel development in Louisiana, which adversely impacts her air and water quality and health and exacerbates the climate impacts she has experienced and will experience in the region.

87. Impacts from climate change and fossil fuel development threaten Jayden's life, liberty, and property. With warmer ocean water temperatures, hurricanes are becoming more frequent and more destructive. Rising sea level means higher storm surges, even from relatively minor storms, which increase coastal flooding, storm damage, and land loss where she lives. Defendants' approval of the dredging of canals through marshes for oil and gas exploration and pipelines has compounded the problem by its destruction of natural storm barriers, increased erosion, and intense saltwater intrusion, resulting in additional land loss. In 2008, during Hurricane Gustav, Jayden's family lost power and water for a week.

88. The air and water pollution from the development of fossil fuels in southern Louisiana also threaten the health of Jayden and her family. Jayden and her family used to enjoy visiting the beach frequently, swimming in the Gulf of Mexico, crabbing, and eating seafood, but she has avoided these activities since the BP oil spill because residual oil is continually dispersed across the Gulf when the increasing number of storms or hurricanes come ashore due to climate change, making such normally enjoyable activities dangerous. Jayden enjoys traveling and visiting family friends all along the Gulf Coast in every state from Texas to Florida and plans to

do so in the future, but the coastal impacts from climate change caused by Defendants, including increased coastal flooding, storm damage, and land loss, will impair her ability to do so in the future.

88-A. Jayden's individual injuries to her personal security, her safety and bodily integrity, her mental health, her home and property, her food and water security, the air she breathes, and her pursuit of happiness in nature, are already occurring. Defendants' national energy system is a substantial cause of those actual injuries.

a. Defendants' national energy system worsens Jayden's individual injuries each year. Jayden is additionally injured by each passing year of losing the ability to prevent the worsening of her injuries. Jayden is also injured by each passing year of losing the ability to prevent the irreversibility and inevitability of a lifetime of worsening hardship to her personal security, her safety and bodily integrity, her mental health, her home and property, her food and water security, the air she breathes, and her pursuit of happiness in nature. The further loss of the ability to protect her life, while suffering these harms, is a separate concrete psychological, emotional, and mental health injury to Jayden. Another separate injury is the deprivation of Jayden's ability to act in her own interest to preserve the window of opportunity to prevent irreversible and inevitable injury going forward and therefore protect her life, all the while suffering these ongoing harms each year from Defendants' national energy system, which they know is causing these injuries. The opportunity to prevent irreversible and inevitable injuries is still available now and is being progressively foreclosed by the ongoing national energy system. When the irreversibility of these harms becomes certain, redress

will be forever foreclosed by this Court or the political majority through the ballot box. Thus, Jayden's injuries stem precisely from Defendants' belief, and resultant policies and practices, that the national energy system is constitutionally compliant.

b. Every attempt Jayden makes to safeguard her life, liberties, property, and equal protection of the law fails because Defendants view the national energy system as constitutionally compliant. As long as Defendants operate under the belief that the national energy system is constitutionally compliant, Defendants will continue to power it with fossil fuels at levels that are dangerous for Jayden and which foreclose her ability to obtain relief that will protect herself. The composition of the United States national energy system is the most important factor in the world as to whether Jayden can prevent her irreversible injury. If the national energy system remains predominantly fossil fuel-based, Jayden will permanently lose her ability to obtain relief that will protect herself and her rights.

c. If this Court should issue a declaratory judgment to resolve this actual constitutional case and controversy between these young Plaintiffs and these government Defendants as to whether Defendants' national energy system has violated and continues to violate Plaintiffs' constitutional rights as described herein, the Court will have ordered a change in legal status that would have practical consequences. A declaratory judgment would significantly increase the likelihood that Jayden would obtain relief to safeguard her life, liberty, property, and equal protection of the law. If the Court declares the nation's energy system unconstitutional in its present form, Defendants will correct the unconstitutional

policies and practices of the national energy system. The worsening of Jayden's injuries at the hands of her government will end, providing substantially meaningful partial redress of her injuries. The Court will thereby preserve Jayden's opportunity to obtain relief to safeguard her life, liberty, property, and equal protection of the law from irreversible and inevitable injury. Protecting the opportunity for freedom and happiness and safety and security, by eliminating a substantial federal government restraint on freedom and decreasing the substantial risk of irreversibility, is tremendously meaningful redress.

89. Plaintiff **Nicholas V.**, by and through his legal guardian and mother, Marie Venner, is a 14-year-old citizen of the U.S. and a resident of Lakewood, Colorado. Nick sees climate change caused by Defendants as a threat to human civilization and has given numerous presentations educating people about the science of climate change. As a Catholic, he is drawn to the intersection between his church and environmental stewardship, and was inspired by Pope Francis's 2015 encyclical, *On Care for Our Common Home*.

90. Pine beetles and wildfires, forcing Nick to stop visiting some of his favorite places, have destroyed forests in Colorado, where Nick used to go hiking, fishing, and camping. Nick enjoys fishing, especially in Boulder Creek, but due to wildfires and variable water flows from droughts and floods, he has not been able to go fishing for the past three years. Nick and his family grow fruit trees, have a garden, and buy food from local farmers. Hail, rainstorms, drought, and pests have ruined their garden several years over the last decade. The unusual weather has affected Nick's consumption of the locally grown produce available through community-supported agriculture. Rising summer temperatures make it harder for Nick to enjoy

outdoor activities, including hiking, biking, and tennis. Warmer winters mean Nick gets to ski less; moreover, when he does go skiing, his favorite parts of the mountain frequently are closed.

90-A. Nick suffers from asthma that is made worse by fossil fuel burning and climate destabilization, especially the increase in the number of very hot days and the extended wildfire and smoke season where Nick lives, breathes, and recreates. Nick's mental health is harmed by both his physical injuries and living in a nation whose government is knowingly harming him and Earth's ability to sustain human life. Nick's individual injuries to his lungs, and his overall physical and mental health, and access to the food, forests, and waters he relies upon for life, sustenance, and happiness are already occurring. Defendants' national energy system is a substantial cause of those actual injuries.

a. Defendants' national energy system worsens Nick's individual injuries each year. Nick is additionally injured by each passing year of losing the ability to prevent the worsening of his injuries. Nick is also injured by each passing year of losing the ability to prevent the irreversibility and inevitability of a lifetime of worsening hardship to his lungs, and his overall physical and mental health, and access to the food, forests, and waters he relies upon for life, sustenance, and happiness. The further loss of the ability to protect his life, while suffering these harms, is a separate concrete psychological, emotional, and mental health injury to Nick. Another separate injury is the deprivation of Nick's ability to act in his own interest to preserve the window of opportunity to prevent irreversible and inevitable injury going forward and therefore protect his life, all the while suffering these ongoing harms each year from Defendants' national energy system, which they know is causing these injuries. The opportunity to prevent

irreversible and inevitable injuries is still available now and is being progressively foreclosed by the ongoing national energy system. When the irreversibility of these harms becomes certain, redress will be forever foreclosed by this Court or the political majority through the ballot box. Thus, Nick's injuries stem precisely from Defendants' belief, and resultant policies and practices, that the national energy system is constitutionally compliant.

b. Every attempt Nick makes to safeguard his life, liberties, property, and equal protection of the law fails because Defendants view the national energy system as constitutionally compliant. As long as Defendants operate under the belief that the national energy system is constitutionally compliant, Defendants will continue to power it with fossil fuels at levels that are dangerous for Nick and which foreclose his ability to obtain relief that will protect himself. The composition of the United States national energy system is the most important factor in the world as to whether Nick can prevent his irreversible injury. If the national energy system remains predominantly fossil fuel-based, Nick will permanently lose his ability to obtain relief that will protect himself and his rights.

c. If this Court should issue a declaratory judgment to resolve this actual constitutional case and controversy between these young Plaintiffs and these government Defendants as to whether Defendants' national energy system has violated and continues to violate Plaintiffs' constitutional rights as described herein, the Court will have ordered a change in legal status that would have practical consequences. A declaratory judgment would significantly increase the likelihood that Nick would obtain relief to safeguard his life, liberty, and equal

protection of the law. If the Court declares the nation's energy system unconstitutional in its present form, Defendants will correct the unconstitutional policies and practices of the national energy system. The worsening of Nick's injuries at the hands of his government will end, providing substantially meaningful partial redress of his injuries. The Court will thereby preserve Nick's opportunity to obtain relief to safeguard his life, liberty, property, and equal protection of the law from irreversible and inevitable injury. Protecting the opportunity for freedom and happiness and safety and security, by eliminating a substantial federal government restraint on freedom and decreasing the substantial risk of irreversibility, is tremendously meaningful redress.

91. [DELETED]

92. Plaintiff **Future Generations, by and through their Guardian Dr. James Hansen,** retain the legal right to inherit well-stewarded public trust resources and to protection of their future lives, liberties, and property – all of which are imminently threatened by the actions of Defendants challenged herein. Guardian Hansen stands in this case both to demand effective governmental action to protect these fundamental rights and, until that is done, a cessation of governmental action that exacerbates the imposed risk.

93. Dr. James Hansen is the former Director of the NASA Goddard Institute for Space Studies, and is presently an Adjunct Professor at Columbia University's Earth Institute, where he directs a program in Climate Science, Awareness, and Solutions. Dr. Hansen trained in physics and astronomy in the space science program of Dr. James Van Allen at the University of Iowa, receiving a bachelor's degree with highest distinction in physics and mathematics, master's degree in astronomy, and Ph.D. in physics in 1967. In his early research Dr. Hansen

used telescopic observations of Venus to extract detailed information on the physical properties of the cloud and haze particles that veil Venus. Since the mid-1970s, Dr. Hansen has focused on studies and computer simulations of the Earth's climate, for the purpose of understanding the human impact on global climate. His testimony on climate change to Congress in the 1980s helped raise broad awareness of the global warming issue.

94. In recent years, Dr. Hansen has drawn attention to the danger of passing climate tipping points, producing irreversible climate impacts that would yield a different planet from the one on which civilization developed. Dr. Hansen has also outlined steps that are needed to stabilize climate. Dr. Hansen's most recent work clearly establishes that danger and those steps, and it is summarized in Dr. Hansen's declaration, which Plaintiffs attach hereto as **Exhibit A**. Dr. Hansen has long advocated for government actions to protect the climate system for present and future generations.

95. Dr. Hansen is an elected member of the United States National Academy of Sciences (1995) and a recipient of the Heinz Award for the Environment (2001), the Leo Szilard Award for Use of Physics for the Benefit of Society (2007), the American Association for the Advancement of Science Award for Scientific Freedom and Responsibility (2007), the Sophie Prize (2010), and the Blue Planet Prize (2010).

95-A. As described above, Youth Plaintiffs are actually harmed in uniquely individual and particularized ways by Defendants' fossil fuel energy policies and practices that make up the national energy system. Youth Plaintiffs are actually harmed physically by the national energy system. Youth Plaintiffs are actually harmed psychologically, mentally, and emotionally by the national energy system. Youth Plaintiffs are also being injured because their federal government continues to put them at greater risk of even more physical and mental health harm than they

already experience, as the policies and practices that make up the national energy system continue and the climate crisis worsens. The United States' ongoing energy system places Youth Plaintiffs at great risk of sustaining additional irreversible physical and mental health harms. The national energy system hastens the irreversibility and worsening of the existing injuries and that hastening in and of itself is an injury to Youth Plaintiffs. Declaratory judgment in Youth Plaintiffs' favor would be substantially likely to stop the United States' hastening of the environmental apocalypse that locks in irreversible injuries to Plaintiffs.

95-B. If the national energy system is not declared unconstitutional, Youth Plaintiffs will disproportionately and irrevocably suffer from the worsening physical and mental health harms caused by the national energy system and the hastening irreversibility of them. If the energy system is not declared unconstitutional, the energy system will inflict additional irreversible and catastrophic harm on these young Plaintiffs. If the energy system is declared unconstitutional, on information and belief, Defendants will take corrective action and change and/or cease the policies and practices that make the national energy system unconstitutional. If the national energy system is declared unconstitutional and Defendants thereafter abide by this Court's declaratory judgment, it is substantially likely that Youth Plaintiffs' injuries will be minimized, reduced to some meaningful extent and in some cases abated entirely. It is also substantially likely that the hastening of the irreversibility of these injuries will slow or cease.

95-C. The systematic conduct making up the national energy system, which has caused and is causing Plaintiffs' ongoing injuries, includes government policies, practices, and aggregate actions, such as permits, licenses, leases, subsidies, standards, and authorizations for the extraction, development, processing, combustion, and transportation of fossil fuel. Until the Court resolves this constitutional controversy, these young Plaintiffs will continue to be harmed

and put at extreme risk by the GHG emissions caused by Defendants' national energy system and Defendants will be free to continue to operate the national energy system to cause harmful GHG emissions in an unconstitutional manner, avoiding the constitutional check of Article III courts and undermining the separation of powers that the Framers intended. Without declaratory relief in the first instance, Defendants will be free to continue this systematic conduct that "may hasten an environmental apocalypse" and carry out "the Nation's willful destruction."

95-D. Declaratory judgment will eliminate the current and substantial legal controversy and inform the parties of the unlawfulness or lawfulness of the government's national energy system, especially as to whether Defendants' policies, practices, and aggregate actions cause a deprivation of rights secured by the Constitution. That declaratory judgment will have immediate practical consequences and will be substantially likely to provide meaningful redress because upon information and belief Defendants will abide by any declaratory judgment order and bring the national energy system into constitutional compliance.

96. Youth Plaintiffs[2] represent the youngest living generation, beneficiaries of the public trust. Youth Plaintiffs have a substantial, direct, and immediate interest in protecting the atmosphere, other vital natural resources, their quality of life, their property interests, and their liberties. They also have an interest in ensuring that the climate system remains stable enough to secure their constitutional rights to life, liberty, and property, rights that depend on a livable future, in other words, a stable climate system capable of sustaining human life. A livable future includes the opportunity to drink clean water, to grow food, to be free from direct and imminent property damage caused by extreme weather events, to benefit from the use of property, and to enjoy the abundant and rich biodiversity of our Nation. Youth Plaintiffs are suffering both

[2] The term "Youth Plaintiffs" refers to each of the individually named Plaintiffs.

immediate and threatened injuries as a result of actions and omissions by Defendants alleged herein and will continue to suffer life-threatening and irreversible injuries without the relief sought. Youth Plaintiffs have suffered and will continue to suffer harm to their health, personal safety, bodily integrity, cultural and spiritual practices, economic stability, food security, property, and recreational interests from the impacts of climate change and ocean acidification caused by Defendants. Youth Plaintiffs have also been denied the procedural right to participate in decision-making regarding the Department of Energy's approval of LNG exports from the Jordan Cove LNG terminal in Coos Bay, Oregon. Youth Plaintiffs, and all of them, have suffered procedural harm as a result of this denial.

97. [DELETED]

DEFENDANTS

98. Defendant **the United States of America** ("United States") is the sovereign trustee of national natural resources, including air, water, sea, shores of the sea, and wildlife. In its sovereign capacity, the United States controls our nation's air space and atmosphere. In its sovereign capacity, the United States controls federal public lands, waters, and other natural resources, including fossil fuel reserves. In its sovereign capacity, the United States controls articles of interstate and international commerce, including extraction, development, and conditions for the utilization of fossil fuels, such as allowing CO_2 emissions from major sources. As a result of both its exercise of control over the national energy system, exercised through its fossil fuel energy policies, practices, and aggregate actions, as well as its failure to limit and phase-out CO_2 emissions, the United States has caused dangerous levels of CO_2 to build up in the atmosphere. That build-up seriously threatens the relatively stable climate system that enabled civilization to develop over the last 10,000 years. It impairs essential national public

trust resources required by Youth Plaintiffs and future generations. This failure to prevent the present and looming climate crisis constitutes a breach in the government's basic duty of care to protect Plaintiffs' fundamental constitutional rights. United States' ongoing energy system places Youth Plaintiffs at great risk of sustaining additional irreversible physical and mental health harms.

99. [DELETED]

100. Defendant **the Office of the President of the United States** includes the Council on Environmental Quality ("CEQ"), the Office of Management and Budget ("OMB"), and the Office of Science and Technology Policy ("OSTP").

a. CEQ's mission is to promote the well-being of our country for both current and future generations, which includes curbing the carbon pollution that is causing climate change.

b. OMB serves as the implementation and enforcement arm of all Presidential policy, including budget development and execution, coordination and review of all significant federal regulations, and issuance of executive orders. OMB promotes the government's affirmative aggregate acts in the areas of fossil fuel production, consumption, and combustion by coordination and review of Federal regulations by executive agencies and review and assessment of information collection requests.

c. OSTP leads interagency efforts to develop and implement sound science and technology policies and budgets, and to work with state and local governments, the scientific community, private sectors, and other nations

toward this end. Pursuant to authority granted by Congress under National Science and Technology Policy, Organization, and Priorities Act of 1976, President Bush's 2001 Executive Order 13226, and President Obama's 2010 Executive Order 13539, OSTP has been involved in the President's strategy for addressing climate change. Despite its charge to ensure that the policies of the Executive are informed by sound science, OSTP has permitted additional fossil fuel projects, including extraction, processing, transportation, combustion, and exportation of coal, oil, and gas from conventional and unconventional reserves.

101. The policies and practices promoted by CEQ, OMB, and OSTP have been contrary to sound science. These policies and practices have led to the current dangerous levels of atmospheric CO_2, dangerous interference with a stable climate system, and violations of Plaintiffs' constitutional rights. Specifically, the policies and practices continue to allow dangerous levels of carbon pollution and, at best, promise very modest future limitations and no near-term CO_2 phase out, as is required to preserve a stable climate system capable of sustaining human life.

102. Defendant **Brenda Mallory** is the current Director of CEQ, and in her official capacity is responsible for all actions of CEQ.

103. Defendant **Shalanda Young** is the current Acting Director of OMB, and in her official capacity is responsible for all actions of OMB.

104. Defendant **Eric Lander** is the current Director of OSTP, and in his official capacity is responsible for all actions of OSTP.

105. Defendant **the United States Department of Energy** ("DOE") is a federal agency whose mission is to advance the national, economic, and energy security of the United States through clean, reliable, and affordable energy; to protect the environment; and to encourage innovations in science and technology that improve the quality of life. DOE's mission statement is to "ensure America's security and prosperity by addressing . . . environmental . . . challenges through transformative science." DOE through the Office of Fossil Energy issues short-term and long-term authorizations for the import and export of natural gas pursuant to authority granted by Congress under the Natural Gas Act of 1938, 15 U.S.C. § 717, as amended by section 201 of the Energy Policy Act of 1992, Pub. L. No. 102-486, § 201, 106 Stat. 2776, 2866. DOE permits domestic energy production and interstate commerce of fossil fuels pursuant to authority granted by Congress under the Department of Energy Organization Act of 1977, 42 U.S.C. § 7112. DOE through the Office of Energy Efficiency and Renewable Energy, regulates the minimum number of light duty alternative fuel vehicles required in certain federal fleets pursuant to authority granted by Congress under the Energy Policy Act of 1992. DOE, through the Building Technology Office, also sets energy efficiency standards, which dictate energy consumption rates for appliances and equipment pursuant to authority granted by Congress under The Energy Policy and Conservation Act, 42 U.S.C. § 6201, as amended.

a. The Federal Energy Regulatory Commission ("FERC"), an agency of DOE, regulates the transmission and sale of electricity and natural gas in interstate commerce; regulates the transportation of oil by pipeline in interstate commerce; reviews proposals for natural gas terminals, pipelines, and storage facilities; ensures the safe operation and reliability

of proposed and operating LNG terminals; and monitors and investigates energy markets.

106. DOE has knowingly failed to perform its duty to transition our nation away from the use of fossil fuel energy. DOE's actions and omissions have substantially contributed to unsafe levels of atmospheric CO_2 and a dangerous climate system.

107. DOE, through the Office of Fossil Energy, issued DOE/FE Order No. 3041, granting long-term multi-contract authorization to export liquefied natural gas by vessel from the Jordan Cove LNG Terminal in Coos Bay.

108. Defendant **Jennifer Granholm** is the current Secretary of Energy and, in her official capacity, is responsible for all actions of DOE.

109. Defendant **the United States Department of the Interior** ("DOI") manages one-fifth of our nation's land, including forests and grazing lands, thirty-five thousand miles of coastline, and 1.76 billion acres of the Outer Continental Shelf. DOI's mission is to protect America's natural resources and heritage, honor cultures and tribal communities, and supply the energy to power the future of our country. DOI claims to be taking the lead in protecting our nation's resources from climate impacts and in managing federal public lands to mitigate climate change.

110. DOI, through the Bureau of Land Management ("BLM"), leases minerals and manages oil and gas development activities on over 570 million acres of federal lands, as well as on private lands where the federal government retained mineral rights, pursuant to the authority granted by Congress in the Mineral Leasing Act of 1920, 30 U.S.C. § 182, as amended, and the Federal Land Policy and Management Act of 1976, 43 U.S.C. § 1719(a). BLM and other federal agencies manage most of the land suitable for oil and gas development in the U.S.

111. DOI, through the Bureau of Ocean Energy Management ("BOEM"), leases the Outer Continental Shelf, the submerged lands, subsoil, and seabed, lying between the seaward extent of the jurisdiction of the States and the seaward extent of Federal jurisdiction, for oil and gas development pursuant to authority granted by Congress under the Outer Continental Shelf Lands Act of 1953, 43 U.S.C. § 1333(a), as amended. As of January 2015, BOEM was administering more than 6,000 active oil and gas leases covering nearly 33 million Outer Continental Shelf acres. Pursuant to authority granted by Congress under the Energy Policy Act of 2005, Pub. L. No. 109-58, 119 Stat. 594, 760, DOI repealed the 160-acre cap on coal leases, allowed the advanced payment of royalties from coal mines, and provided incentives to companies to drill for oil in the Gulf of Mexico.

112. Through its policies and practices in permitting the extraction of coal, coal-bed methane, oil, oil-shale and natural gas, and oil, coal and electric infrastructure and transmission facilities, and logging, livestock grazing, and off-road vehicle use on public land, the DOI is substantially contributing to dangerous levels of atmospheric CO_2 and a dangerous climate system in our Nation.

113. Defendant **Deb Haaland** is the current Secretary of Interior and, in her official capacity, is responsible for all actions of DOI.

114. Defendant **the United States Department of Transportation** ("DOT") is a federal agency overseeing this Nation's aviation, road, highway, railway, truck, and marine transportation infrastructure. DOT's regulations of emissions related to that infrastructure play a vital role in the Federal Government's response to climate change.

a. DOT, through the Federal Aviation Administration, the Federal Highway Administration, and the Pipeline and Hazardous Materials Safety

Administration, oversees and regulates the spending programs that finance construction and maintenance of our nation's transportation infrastructure, pursuant to authority granted by Congress under the Department of Transportation Act of 1966, 49 U.S.C. § 305, as amended.

b. DOT, through the National Highway Traffic Safety Administration, sets fuel economy standards for U.S. vehicle manufacturers, pursuant to authority granted by Congress under the Energy Policy and Conservation Act of 1975, Pub. L. No. 94–163, § 301, 89 Stat. 902, 903, 905, as amended by the Energy Independence and Security Act of 2007, 49 U.S.C. § 32902.

115. With the power to regulate the means of transportation throughout our country, DOT has the responsibility to ensure that all modes of transportation use only clean energy and eliminate dangerous carbon pollution. Further, DOT permits the transport of fossil fuels via truck and rail. DOT's stated mission is to "[enhance] the quality of life of the American people, today and into the future." DOT acknowledges the severity of the threats of climate change, yet continues to facilitate the severity of climate change impacts by contributing approximately 27% of U.S. CO_2 emissions in 2013.

116. Defendant **Pete Buttigieg** is the current Secretary of Transportation and, in his official capacity, is responsible for all DOT policies and practices.

117. Defendant **the United States Department of Agriculture** ("USDA") is a federal agency whose vision statement expresses the agency's goal to preserve and conserve our nation's natural resources. USDA's mission statement states that it will use the best available science as it carries out its responsibilities in caring for natural resources. USDA has authority over our

nation's food and agriculture, as well as many natural resources, including national forests, which serve the vital role of absorbing CO_2 from our atmosphere—commonly referred to as "carbon sequestering."

a. USDA, through the U.S. Forest Service, authorizes 25% of U.S. coal production.

b. The U.S. Forest Service, along with BLM, coordinates and authorizes the leasing of federal public lands for the extraction of oil and gas pursuant to authority granted by Congress under the Mineral Leasing Act of 1920, as amended by both the Federal Onshore Oil and Gas Leasing Reform Act, and the Mineral Leasing Act for Acquired Lands. The U.S. Forest Service, in conjunction with BLM, issues leases and mining permits for coal mining development and oversees coal mining on federal public lands pursuant to authority granted by Congress, under the Mineral Leasing Act of 1920, as amended, and the Surface Mining Control and Reclamation Act of 1977, 30 U.S.C. § 1273.

c. USDA's Forest Service Minerals & Geology Management division manages and oversees aspects of the development and production of energy and mineral resources, including authorizing ancillary projects such as roads and pipelines that are part of the energy and minerals development projects of USDA.

d. USDA has substantially contributed to and continues to substantially contribute to a dangerous climate system by permitting large-scale logging in national forests, by supporting polluting farming and agricultural

practices, and by authorizing fossil fuel extraction and use under its jurisdiction. USDA has not protected the nation's National Forest System as a carbon sink.

118. Defendant **Thomas J. Vilsack** is the current Secretary of Agriculture and, in his official capacity, is responsible for all actions of the USDA.

119. Defendant **the United States Department of Commerce** ("Commerce") is a federal agency that is supposed to promote sustainable development. Commerce has authority over the monitoring equipment for greenhouse gas ("GHG") emissions, giving it direct oversight of our nation's industries and emissions pursuant to authority granted by Congress under Title 15 of the United States Code.

a. Commerce, through National Institute of Standards and Technology, oversees research in energy efficiency opportunities for homes and companies nationwide.

b. Commerce, through the International Trade Administration's Office of Energy and Environmental Industries, promotes fossil fuel export opportunities, including identifying for the fossil fuel industry oil and gas markets where export activities can make the biggest impact, pursuant to authority granted by Congress, under the Reorganization Plan No. 3 of 1979.

c. Commerce, through the Bureau of Industry and Security ("BIS"), authorizes and administers the rules governing crude oil exports pursuant to 15 C.F.R. § 754.2. BIS issues permits to export crude oil to all destinations, including Canada.

d. Commerce, through the National Oceanic and Atmospheric Administration, is charged with overseeing the preservation and protection of the oceans and the atmosphere pursuant to authority granted by Congress under the Reorganization Plan No. 4 of 1970.

e. Commerce has abrogated its duty to preserve and protect the atmosphere and other natural resources under its jurisdiction and has not prevented the waste of the public trust in the atmosphere and oceans.

120. Defendant **Gina Raimondo** is the current Secretary of Commerce and, in her official capacity, is responsible for all actions of Commerce.

121. Defendant **the United States Department of Defense** ("DOD") is a federal agency charged with ensuring the security of this nation. DOD considers climate change a threat multiplier for its potential to exacerbate many challenges confronting our nation, including infectious disease, regional instability, mass migrations, and terrorism. Climate change has impacted and will continue to impact all military installations, as well as the DOD's supply chains, equipment, vehicles, and weapon systems.

a. DOD is our nation's largest employer and is responsible for significant carbon pollution from both its vehicle fleet, and its 500 bases of military infrastructure, including 300,000 buildings totaling 2.2 billion square feet.

b. For all exports of coal, oil, and gas by ship, the DOD's Army Corps of Engineers authorizes marine export facilities, pursuant to the Clean Water Act and the Rivers & Harbors Act. The Army Corps of Engineers also maintains international navigation channels, including the navigation channel at Coos Bay, pursuant to authority granted by Congress under the

Rivers & Harbors Act. Such exports endanger the climate system on which our nation and plaintiffs alike depend.

122. Defendant **Lloyd Austin** is the current Secretary of Defense and, in his official capacity, is responsible for all actions of DOD.

123. Defendant **the United States Department of State** ("State Department") is a federal agency whose stated mission is to "shape and sustain a peaceful, prosperous, just, and democratic world and foster conditions for stability and progress for the benefit of the American people and people everywhere." The State Department plays a lead role in Defendants' response to climate change. The State Department prepared the 2014 U.S. Climate Action Report, which states that the Federal Government is "committed to continuing enhanced action . . . to lead the global effort to achieve a low-emission, climate resilient future."

a. The State Department leads international efforts on climate change on behalf of the Office of the President.

b. The State Department, through the Office of the Special Envoy for Climate Change is the Administration's chief climate negotiator. In 2009, Special Envoy for Climate Change Todd Stern stated: "The costs of inaction—or inadequate actions—are unacceptable. But along with this challenge comes a great opportunity. By transforming to a low-carbon economy, we can stimulate global economic growth and put ourselves on a path of sustainable development for the 21st century."

c. The Secretary of State receives all applications for Presidential Permits for the construction, connection, operation, or maintenance, at the borders of the United States, of facilities for the exportation or importation of

petroleum, petroleum products, coal, or other fuels, including hazardous liquids to or from a foreign country, and is required to issue a Presidential Permit if such exportation would serve the national interest, under Executive Order 13337, and pursuant to 3 U.S.C. § 301. Specifically, the State Department has jurisdiction over all cross-border oil pipelines, and in the last decade has been considering and approving longer cross-border projects, including those transporting oil sands crude, otherwise known as tar sands. All petroleum products entering and leaving the U.S. by pipeline do so under State Department approval. Currently there are at least 13 active Presidential Permits for oil pipelines. The State Department has consistently approved such permits, even though it has full authority and discretion to deny them where fossil fuel projects endanger the nation by causing or enhancing dangerous climate change.

124. Defendant **Antony Blinken** is the current Secretary of State and, in his official capacity, is responsible for all actions of the State Department.

125. Defendant **the United States Environmental Protection Agency** ("EPA") permits and regulates the activities, industries, and sources of carbon pollution in the U.S. under the Clean Air Act, the Clean Water Act, the Comprehensive Environmental Response, Compensation, and Liability Act, the Safe Drinking Water Act, and the Resource Conservation and Recovery Act. The stated mission of the EPA is to protect human health and the environment and ensure that the Federal Government's actions to reduce environmental risks are based on the best available science. EPA sets CO_2 standards for power plants, which account for our nation's largest source of CO_2 emissions at 37% of U.S. annual emissions. EPA has

authorized, and continues to authorize installations and activities that emit prodigious amounts of CO_2, which authorizations dangerously disrupt and fail to preserve a habitable climate system – in violation of Plaintiffs' fundamental rights.

a. EPA, through the Office of Ground Water and Drinking Water and the Office of Science and Technology, exempts oil and gas producers from certain requirements of the Safe Drinking Water Act (thereby easing regulatory burdens to oil and gas development), pursuant to authority granted by Congress, under the Energy Policy Act of 2005.

126. EPA abrogated its duty to implement its 1990 Plan, entitled "Policy Options for Stabilizing Global Climate," to reduce CO_2 emissions (a pollutant under its jurisdiction) in line with the best available science, and continues to allow CO_2 emissions in excess of what is necessary for climate stability.

127. That failure is not allayed by EPA's August 3, 2015 final "Clean Power Plan" because CO_2 emissions reductions projected under the "Clean Power Plan" do not even approach the rate required to preserve a habitable climate system. First, the "Clean Power Plan" affects emissions only in the power sector. Second, the "Clean Power Plan" aims for power plant emissions reductions of only approximately 32% from 2005 levels by full implementation in 2030. Those power plant emission reductions from 2005 levels would achieve only an 8-10% reduction in total U.S. emissions by 2030. The annualized emissions reduction rate is thus, even accepting EPA's biased math, approximately 1.25% per year, a reduction rate that is a fifth of that minimally required to preserve a habitable climate system. Moreover, nearly half of the EPA-asserted emission reduction was already realized in the 2005-2014 period, namely *before* the "Clean Power Plan" was finalized. Furthermore, upon information and belief, the "Clean

Power Plan" will allow fossil fuel-fired power units to continue to operate and will encourage increased investment in, utilization, and reliance on natural gas (whose principle constituent, methane, is a highly potential greenhouse gas). The "Clean Power Plan," moreover, does nothing to halt or otherwise diminish fossil fuel extraction, production, and exportation in the United States, fails even to return U.S. emissions to 1990 levels, and continues to allow CO_2 emissions far in excess of what is minimally required to secure a stable climate system. EPA's "Clean Power Plan," accordingly, is not an adequate or proportionally appropriate response to the climate crisis. By allowing emissions to continue at dangerous levels, EPA continues to jeopardize the climate system on which Plaintiffs depend, now and in the future.

128. Defendant **Michael Regan** is the current Administrator of EPA and, in his official capacity, is responsible for all actions of EPA.

129. Pursuant to its policies and practices that make up the national energy system, Defendants have permitted, authorized, and subsidized the extraction, production, transportation, and utilization of fossil fuels through aggregate actions across the U.S. (and beyond). Defendants retain authority to limit or to deny that extraction, production, transportation, and utilization of fossil fuels, and otherwise to limit or prohibit their emissions. The vastness of our nation's fossil fuel enterprise renders it infeasible for Plaintiffs to challenge every instance of Defendants' violations and, even if feasible, challenging each of Defendants' actions would overwhelm the court. Nonetheless, Defendants' liability arises from the policies and practices that make up Defendants' national energy system. The national energy system has substantially caused the present climate crisis and Plaintiffs' injuries.

130. Director Brenda Mallory, Acting Director Shalanda Young, Director Eric Lander, Secretary Jennifer Granholm, Secretary Deb Haaland, Secretary Pete Buttigieg, Secretary

Thomas J. Vilsack, Secretary Gina Raimondo, Secretary Lloyd Austin, Secretary Antony Blinken, and Administrator Michael Regan, through their respective offices, departments, and agencies, CEQ, OMB, OSTP, DOE, DOI, DOT, USDA, Commerce, DOD, State Department, and EPA, are primarily responsible for the United States' energy system through authorizing, permitting, and incentivizing fossil fuel production, consumption, transportation, and combustion, causing the atmospheric CO_2 concentration to increase to at least 400 ppm and, thus, substantial harm to Plaintiffs. Defendants have failed to preserve a habitable climate system for present and future generations, and instead have created dangerous levels of atmospheric CO_2 concentrations. The national energy system and the affirmative aggregate acts, omissions, and policies and practices of Defendants that make up the national energy system, jointly and severally, have violated and continue to violate Plaintiffs' fundamental constitutional rights to freedom from deprivation of life, liberty, and property; Plaintiffs' constitutional rights to equal protection; Plaintiffs' unenumerated inherent and inalienable natural rights; and Plaintiffs' rights as beneficiaries of the federal public trust.

STATEMENT OF FACTS

I. THE FEDERAL GOVERNMENT HAS KNOWN FOR DECADES THAT CARBON DIOXIDE POLLUTION WAS CAUSING CATASTROPHIC CLIMATE CHANGE AND THAT MASSIVE EMISSION REDUCTIONS AND A NATION-WIDE TRANSITION AWAY FROM FOSSIL FUELS WAS NEEDED TO PROTECT PLAINTIFFS' CONSTITUTIONAL RIGHTS.

131. As early as 1899, scientists understood that CO_2 concentrations in the atmosphere cause heat retention on Earth and that a doubling or tripling of the CO_2 content in 1899 would significantly elevate Earth's surface temperature. Scientists also understood that CO_2 was the determinative factor for global heating. By the turn of the 20th Century, it was widely accepted in the scientific community that increasing the atmospheric concentration of CO_2 could cause global climate change.

132. By 1965, the Executive Branch reported that anthropogenic pollutants, including CO_2, impair our nation's economy and its quality of life. In the 1965 Report of President Lyndon Johnson's Scientific Advisors, "Restoring the Quality of Our Environment," the White House confirmed that anthropogenic pollutants, including CO_2, threaten "the health, longevity, livelihood, recreation, cleanliness and happiness of citizens who have no direct stake in their production, but cannot escape their influence."

133. For fifty years, the Executive Branch has known that "pollutants have altered on a global scale the CO_2 content of the air" through "the burning of coal, oil and natural gas." The Executive Branch predicted that CO_2 "will modify the heat balance of the atmosphere to such an extent that marked changes in climate, not controllable th[r]ough local or even national efforts, could occur." The Executive Branch warned that "carbon dioxide [gases] are accumulating in such large quantities that they may eventually produce marked climatic change."

134. Fifty years ago, the Executive Branch described the marked climatic changes from CO_2 pollution as including the melting of the Antarctic icecap, rising sea levels, warming oceans, acidifying waters, and additional releasing of CO_2 and methane due to these events. It recommended reducing the heating of the Earth because of the extraordinary economic and human importance of our climate system.

135. Fifty years ago, the White House recommended that a tax system be implemented to tax polluters, including air pollution, "in proportion to their contribution to pollution" to incentivize pollution reduction.

136. In 1969, Patrick Moynihan, then-Adviser to President Nixon, wrote a letter to White House counsel John Ehrlichman stating that CO_2 pollution resulting from burning fossil fuels was a problem perhaps on the scale of "apocalyptic change," threatening the loss of cities

like New York and Washington D.C. from sea level rise. The 1969 Moynihan Letter urged the Federal Government to immediately address this threat.

137. In 1978, Congress passed the National Climate Program Act "to establish a national climate program that will assist the Nation and the world to understand and respond to natural and man-induced climate processes and their implications." 15 U.S.C. § 2901(3).

138. On June 23, 1988, Plaintiff-Guardian Dr. James Hansen, then Director of NASA's Institute for Space Studies and a leading climate scientist in the Federal Government, testified before Congress that carbon pollution in the atmosphere was causing global warming and that impacts were already being observed.

139. Around the time of Dr. Hansen's testimony, Congress directed its own offices and EPA to separately prepare reports on how to stabilize the global climate system and transition our country away from the use of fossil fuels.

140. In response, in December 1990, EPA submitted a report to Congress on "Policy Options for Stabilizing Global Climate." The EPA's 1990 Report concluded: "responses to the greenhouse problem that are undertaken now will be felt for decades in the future, and lack of action now will similarly bequeath climate change to future generations."

141. The EPA's 1990 Report called for a 50% reduction in total U.S. CO_2 emissions below 1990 levels by 2025. EPA explained that such reductions were the only pathway to achieve Congress' goal of stopping global warming and stabilizing the climate system. The EPA's 1990 Report also called for stabilizing atmospheric CO_2 concentrations at 350 ppm, the current level of that time, a response to the congressional objective that total global warming not exceed 1.5° C above the preindustrial level. In its 1990 Report, EPA confirmed the Executive Branch's findings from 1965 that CO_2 was a "dangerous" pollutant.

142. In 1991, promptly following EPA's 1990 Report, the Congressional Office of Technology Assessment ("OTA") delivered to Congress its own report, "Changing By Degrees: Steps to Reduce Greenhouse Gases." Finding the United States was the single largest contributor to carbon pollution, the OTA's 1991 Report developed "an energy conservation, energy-supply, and forest-management package that can achieve a 20- to 35-percent emissions reduction" through a mix of regulatory and market-based federal policies, in order to prevent global warming and climate change. OTA reported that, if its "package" was implemented, the Federal Government could lower CO_2 emissions 35% from 1987 levels by 2015 and possibly save the Federal Government $20 billion per year. OTA determined that the 35% necessary reduction in CO_2 emissions was only the beginning and further efforts in the 21st century would be required to stabilize our nation's climate system.

143. The OTA's 1991 Report stated that major reductions of CO_2 would require significant new initiatives by the Federal Government and must be sustained over decades, even before all the scientific certainties are resolved: "[I]t is clear that the decision to limit emissions cannot await the time when the full impacts are evident. The lag time between emission of the gases and their full impact is on the order of decades to centuries; so too is the time needed to reverse any effects." The OTA's 1991 Report informed Congress that the level of emission reductions needed would require the country to wean itself from fossil fuels. OTA also urged that, while global warming was a problem on a global scale, U.S. leadership was critical to solving the problem and would seriously impact what happened around the globe.

144. Concluding that actions would be required across the federal government, both the EPA's 1990 Report and the OTA's 1991 Report concluded that an essential component of reducing CO_2 emissions was implementing a rising carbon tax.

145. On October 15, 1992, following receipt of the EPA and OTA Reports, the Senate ratified the United Nations Framework Convention on Climate Change ("UNFCCC"). The UNFCCC was executed to "protect the climate system for the benefit of present and future generations of humankind." The UNFCCC evidences an "overwhelming weight" of support for protection of the atmosphere under the norms and principles of intergenerational equity. UNFCCC, Art. 3. The minimal objective of the UNFCCC is the "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner." UNFCCC, Art. 2.

146. The recommendations in the EPA's 1990 Report ("Policy Options for Stabilizing Global Climate") and the OTA's 1991 Report ("Changing By Degrees: Steps to Reduce Greenhouse Gases") were never implemented. U.S. fossil fuel production, consumption, and combustion all continued to accelerate at dangerous speeds for decades.

147. On December 7, 2009, nearly 17 years after the United States ratified the UNFCCC, the then-Administrator of EPA, Lisa Jackson, issued EPA's formal endangerment finding under the Clean Air Act. The finding stated that current and projected atmospheric concentrations of greenhouse gases including, in particular, CO_2, threatened the public health and welfare of current and future generations. EPA issued its endangerment determination only after being compelled to do so by the U.S. Supreme Court in *Massachusetts v. EPA*, 549 U.S. 497 (2007).

148. On January 2, 2011, EPA commenced partial regulation of greenhouse gases under the Clean Air Act from mobile and stationary sources of air pollution.

149. More than two decades have passed since the EPA's 1990 Report and the OTA's 1991 Report were issued to Congress. Little has been accomplished in the way of phasing out emissions even though, as DOE admits in its strategic plan, "our responsibility to future generations is to eliminate most of our carbon emissions and transition to a sustainable energy future."

150. During the last decade, Defendants have repeatedly stated that allowing "business as usual" CO_2 emissions will imperil future generations with dangerous and unacceptable economic, social, and environmental risks. As Defendants have acknowledged, the use of fossil fuels is a major source of these emissions, placing our nation on an increasingly costly, insecure, and environmentally dangerous path.

II. IN SPITE OF KNOWING OF THE SEVERE DANGERS POSED BY CARBON POLLUTION, DEFENDANTS CREATED AND ENHANCED THE DANGERS THROUGH FOSSIL FUEL EXTRACTION, PRODUCTION, CONSUMPTION, TRANSPORTATION, AND EXPORTATION

A. Despite the Known Danger, Defendants Caused Climate Instability and Allowed U.S. Fossil Fuel Extraction, Production, Consumption, Transportation, and Exportation and Associated Emissions, to Dangerously Increase

151. Through its policies, practices, and aggregate acts, the United States has long had and continues to have a national energy system that has made fossil energy the dominant form of energy used in the United States. In 2014, over 80% of U.S. energy comes from fossil fuels. Between 1751 and 2014, the United States has been responsible for emitting 25.5% of the world's cumulative CO_2 emissions to the atmosphere from within its borders. Those emissions do not account for the embedded emissions in imported goods and materials that are consumed in the United States. Defendants enabled and permitted those cumulative emissions.

152. In the last fifty years, total U.S. production and consumption of fossil fuels drastically increased.

153. Acting with deliberate indifference, Defendants have not implemented, or complied with, the EPA's 1990 Report and the OTA's 1991 Report to reduce carbon pollution from fossil fuels, stop global warming, and protect the climate system for future generations. Had Defendants followed the EPA's 1990 Report and the OTA's 1991 Report, CO_2 emissions today would be reduced by 35% from 1987 levels. Instead, since 1991, Defendants have knowingly allowed at least an additional 130,466 million metric tons of CO_2 emissions from fossil fuel combustion.

154. Accordingly, instead of pursuing their own plans to slash emissions and reduce the risk of dangerous climate change, Defendants knowingly acted to exacerbate that risk and impose harm on the nation and on Plaintiffs.

155. Total Fossil fuel production in the U.S. climbed to 65.244 Quadrillion Btu in 2014, up substantially from such consumption in 1965.

U.S. Primary Energy Production by Source (Quadrillion Btu)				
Year	**Coal**	**Natural Gas**	**Petroleum**	**Fossil Fuels**
1965	13.055	15.775	16.521	45.351
1991	21.636	18.229	15.701	55.566
2014	20.287	26.516	18.441	65.244

156. Total Fossil fuel energy consumption in the U.S. climbed to 80.366 Quadrillion Btu in 2014, up substantially from such consumption in 1965.

U.S. Primary Energy Consumption by Source (Quadrillion Btu)				
Year	**Coal**	**Natural Gas**	**Petroleum**	**Fossil Fuels**
1965	11.581	15.769	23.246	50.596
1991	18.992	20.033	32.846	71.871
2014	17.991	27.592	34.783	80.366

157. Fossil fuel emissions from energy consumption in the U.S. climbed to 5.4 billion metric tons of CO_2 in <u>2014</u>, up substantially from such emissions in <u>1965</u>.

U.S. CO2 Emissions From Energy Consumption by Source (Million Metric Tons of CO2)				
Year	**Coal**	**Natural Gas**	**Petroleum**	**Total Fossil Fuels**
1965	1,075	828	1,483	3,386
1991	1,807	1,047	2,005	4,859
2014	1,713	1,441	2,249	5,404

158. In <u>2011</u>, fossil fuel combustion in the U.S. accounted for 94% of CO_2 emissions.

159. The above emissions figures are from U.S. Government sources and, regrettably, underreport the amount of emissions that Defendants' actions have substantially caused. EPA uses a sector-based emission inventory, upon which the other Defendants also rely. A sector-based emission inventory accounts only for in-boundary emissions, and not those attributed to embedded emissions – emissions that account for the consumption of goods imported to the U.S. Defendants have not provided a national consumption-based inventory for CO_2 emissions, which would include all embedded CO_2 emissions for goods produced outside of the U.S. and consumed within the U.S.

160. In 2012, the U.S. was the largest producer of natural gas, producing a total that year of 24,058 billion cubic feet (Bcf). Also in 2012, the U.S. was second in "Total Primary Coal Production," with 1,016,458 thousand short tons; second in "Total Primary Energy Production," producing 79.212 Quadrillion Btu; and second in "Total Primary Energy Consumption," consuming 95.058 Quadrillion Btu.

161. In 2014, according to the United States Energy Information Administration ("EIA"), the U.S. was the largest producer of total petroleum and other liquids with 13,973 thousand barrels produced per day.

162. The U.S. is by far the dominant producer of both shale gas and tight oil in the world. Also, the U.S. is one of four countries in the world that is producing commercial volumes of either natural gas from shale formations (shale gas) or crude oil from shale formations (tight oil).

163. The aggregate actions by Defendants in allowing fossil fuel production, consumption, and emissions to increase in the U.S. since 1965 ignored science driven considerations of climate system protection. These aggregate actions were taken with deliberate indifference to the need for a national carbon budget or a national plan that includes an analysis of the cumulative impacts of Defendants' actions upon the climate system and with respect to the fundamental rights of the present and future generations.

B. Defendants Have Allowed Excessive Fossil Fuel Production on Federal Public Lands.

164. In 2013, 25% of all fossil fuels extracted in the U.S. originated on federal public lands.

165. In 2014, Defendant United States, through the President, DOI through BLM, DOD through Army Corps of Engineers, and EPA, authorized and oversaw the sale of 421 million tons of coal from federally-leased lands.

166. Since January 1990, DOI through BLM has leased 107 coal tracts, and associated coal production and revenues have grown. In 2015, the BLM reported that approximately 40% of all coal produced in the United States comes from federal lands. The United States has more coal deposits available than any other fossil fuel resource within its borders and, as of 2015, has 28% of the world's coal reserves.

167. In 1985, there were 18,849 recorded federal producing oil and gas leases issued by DOI through BLM. By 2014 there were 23,657 recorded federal producing oil and gas leases issued by DOI through BLM.

168. As of June 2014, DOI's BLM has authorized approximately 47,000 oil and gas leases on public lands, and approximately 95,000 oil and gas wells, with an additional 3,000 wells drilled annually by the oil and gas industry. The BLM oversees approximately 700 million subsurface acres of mineral estate. There are currently 36 million acres of federal land under lease for potential fossil fuel development in 33 states, pursuant to DOI's BLM authorization.

169. From 2009-2011, the President and DOI through BLM processed more applications for permits to drill oil and gas, despite receiving far fewer applications, than the prior administration from 2006-2008.

170. Since 1985, DOI through BLM has issued between 1,486 to 6,617 permits annually to drill on federal lands. BLM has approved approximately 99% of all received applications for permits to drill, without taking into consideration that such permits would endanger Plaintiffs or increase Plaintiffs' susceptibility to harm.

C. Defendants Subsidize the Fossil Fuel Industry

171. In addition to leasing federal public lands for fossil fuel exploitation, the United States subsidizes, funds, and subsidizes fossil fuel production and consumption.

172. The United States subsidizes the fossil fuel industry by undervaluing royalty rates for federal public leasing, as well as through royalty relief resulting in the loss of billions of dollars of foregone revenue. U.S. royalty rates are consistently less than state royalty rates. For example, Texas's royalty rate for leasing is double the federal percentage.

173. Through eleven federal fossil fuel production tax provisions, the United States incurs approximately $4.7 billion in annual revenue costs. Through a fossil fuel consumption subsidy, the United States annually forgoes approximately $3.4 billion in revenue.

174. The United States provides approximately $5.1 billion per year in tax provision subsidies to support fossil-fuel exploration.

175. Two tax code provisions for the benefit of the fossil fuel enterprise were introduced in the early 1900s. These provisions are still in place today, resulting in substantial revenue losses. The "intangible drilling costs" provision was introduced in 1916, 26 U.S.C. § 263(c); in 1926 the "percentage depletion allowance" provision was introduced, 26 U.S.C. § 613.

176. According to the International Monetary Fund ("IMF"), the United States is the world's top subsidizer of fossil fuels, in absolute terms, in the amount of $502 billion per year, which includes the IMF's accounting of negative externalities.

177. The United States has supported fossil fuel development through overseas public financing, primarily through the Export-Import Bank of the United States, an agency of the Office of the President. For example, through the Export-Import Bank of the United States, the Office of the President provided $14.8 billion in commitments for 78 transactions or projects in

the petroleum sector, including 49 transactions in Latin American, 14 in Africa, six in Russia/FSU, five in the Middle East, and four in Asia. In fiscal year 2010, the Export-Import Bank of the United States provided approximately $3 billion in financing for the Papua New Guinea LNG Project or Papua New Guinea Liquefied Natural Gas Project and $18 million for the Sangatta Surface Coal Mine in Indonesia. The Export-Import Bank of the United States also supported numerous coal and gas power plants.

178. The United States supports fossil fuel development by allowing the fossil fuel industry to avoid the true social cost of CO_2 emissions from fossil fuels. Based on EPA's social cost of carbon estimates, CO_2 emissions from fossil fuels have the potential to cause trillions of dollars in damages.

D. Defendants Recklessly Allow Interstate and International Transport of Fossil Fuels

179. Despite knowledge of the harm to Plaintiffs caused by the CO_2 emissions from fossil fuels, Defendants recklessly allow all interstate transport of fossil fuels. Despite knowledge of the harm to Plaintiffs caused by the CO_2 emissions from fossil fuels, Defendants recklessly authorize and/or permit the exportation and importation of fossil fuels and/or the facilities allowing the exports and imports of fossil fuels.

180. The Office of the President exercises permitting authority over the construction and operation of "pipelines, conveyor belts, and similar facilities for the exportation or importation of petroleum, [and] petroleum products." President Obama has failed to dismantle the U.S. fossil fuel edifice, adding an additional 100,000 miles to the 2.5 million miles of oil and gas pipelines within the nation.

181. A presidential exemption or federal license is required for all exports of crude oil to all destinations. In 2014, DOE oversaw the importation of 2,677,911 thousand barrels of

crude oil, and Commerce through BIS authorized the exportation of 126,152 thousand barrels of crude oil, both increases from 2013.

182. No natural gas can be exported or imported without DOE authorization through FERC. FERC permits all LNG export terminals, including Jordan Cove LNG Terminal. Since 1995, the U.S. has imported 71,730 Bcf of natural gas and exported 14,623 Bcf. In 2014, through DOE's authorization, 51,824 thousand barrels of natural gas plant liquids and liquefied refinery gases were imported and 257,948 thousand barrels of natural gas plant liquids and liquefied refinery gases were exported.

183. Although in 1975 Congress authorized the Office of the President to restrict coal exports under the Energy Policy and Conservation Act of 1975, 42 U.S.C. § 6212(a), the President has not exercised this authority to impose any significant export restrictions on coal. In fact, since 1990, the United States has promoted expanding coal exports. Coastal facilities through which coal may be exported are subject to federal approvals. In the Pacific Northwest alone, three new marine coal terminal projects are under various stages of federal permitting and review.

184. In 2011, the U.S. exported 107 million short tons of coal. In 2012, U.S. coal exports totaled 125 million short tons, the highest level of coal exports in over twenty years. Most recently, in 2014 the EIA reported that the U.S. imported 11 million short tons of coal and exported 97 million short tons of coal.

E. Defendants Recklessly Allow CO_2 Pollution From Combustion of Fossil Fuels

185. Either directly or through the control of the Federal Government, Defendants authorize the combustion of all fossil fuels in the U.S., including coal, oil, and gas. Such

combustion occurs primarily in the energy and refineries sector, the transportation sector, and the manufacturing sector.

186. In 2012, petroleum accounted for 36.5% of the total primary energy consumption in the U.S., the single largest source of energy consumption. All U.S. petroleum refineries are permitted and regulated by EPA.

187. In 2013, fossil fuel combustion from various industrial processes accounted for approximately 15% of total CO_2 emissions in the U.S. The EPA regulates these industrial processes.

188. The DOE establishes efficiency standards in buildings and appliances. These standards affect levels of energy consumption and combustion.

189. Since 1975, through the Corporate Average Fuel Economy ("CAFE") program, the United States has required manufacturers of vehicles sold in the U.S. to comply with fuel economy standards set by DOT. By controlling the fuel economy standards, Defendants have exercised control over CO_2 emissions in the transportation sector.

190. From 1996-2014, through tax breaks, the United States subsidized the purchase, and thus increased demand for, vehicles weighing more than 6,000 pounds ("SUVs"). SUVs are less fuel-efficient and emit greater quantities of CO_2 per mile than lighter-weight vehicles, other factors held equal.

191. In 2012, U.S. CO_2 equivalent emissions from transportation were 1,837 million metric tons. In 2012, CO_2 equivalent emissions from transportation of all vehicles in the U.S., including aviation, passenger cars, SUVs, heavy-duty trucks, freight rail, ships, and boats, were responsible for 28% of total U.S. greenhouse gas emissions.

III. THE JORDAN COVE LNG EXPORTS

192. Enacted in 1992, Section 201 of the Energy Policy Act mandates the authorization of natural gas imports from, or exports to, a nation with which the United States has a free trade agreement, without modification or delay, to any person applying for such authorization. Accordingly, under the Energy Policy Act, such natural gas imports and exports are automatically deemed consistent with the public interest. 15 U.S.C. § 717b(c).

193. Pursuant to Section 201 of the Energy Policy Act, on December 7, 2011, DOE, through the Office of Fossil Energy, issued DOE/FE Order No. 3041, granting long-term multi-contract authorization to Jordan Cove Energy Project, L.P. to export liquefied natural gas from Jordan Cove LNG Terminal in Coos Bay, Oregon, to free trade agreement nations. The DOE/FE Order authorizes the export of up to 13,140 Bcf of natural gas over 30 years. That quantity of natural gas would result in approximately 716.2 million metric tons of CO_2 emissions, more than all of the CO_2 emitted in 2012 by our nation's largest emitter, Texas.

194. Jordan Cove will be operational in the first quarter of 2018, according to the Vice President of the Jordan Cove Energy Project, LLC, seven years after receiving its export authorization from DOE.

195. Pursuant to its authorization, the Jordan Cove LNG L.P. has given notice to DOE that, by the end of 2015, even before it has all final approvals from other agencies, it will enter into "binding long-term liquefaction tolling service agreements" for the full liquefaction capacity of the export terminal.

196. The sources of natural gas for Jordan Cove LNG's exports authorized by DOE include suppliers operating in the Rocky Mountain region of the U.S., western Wyoming, northwestern Colorado, northern Utah, northern Nevada, and northern California.

197. In a letter of support for Jordan Cove LNG Terminal exports, Governor John Hickenlooper of Colorado wrote to DOE and FERC: "Jordan Cove is of specific interest to Colorado . . . The project terminal is the only LNG facility on the west coast that would directly link Colorado to new energy markets via the Ruby Pipeline which originates in northwest Colorado and carries natural gas from that region to states further west of Colorado."

198. Jordan Cove LNG will liquefy this natural gas for export at its proposed LNG export terminal in Coos Bay, Oregon. Jordan Cove plans to build a new power plant to provide the additional electricity needed to liquefy the natural gas for export. The proposed 420-MW South Dunes Power Plant would be the second-largest single source of greenhouse gas emissions in Oregon and would be the largest single source of CO_2 emissions in Oregon in 2020 if it were built. The Jordan Cove South Dunes Power Plant would emit 51.6 million tons of CO_2 over 30 years, or 1.72 million tons of CO_2 per year.

199. According to the EIA, liquefying natural gas requires the energy equivalent of 10% of the gas being exported.

200. The CO_2 emissions resulting from the Jordan Cove LNG Terminal exports and the South Dunes Power Plant emissions will harm Youth Plaintiffs who live in and around Oregon, as well as Future Generation Plaintiffs, by further endangering the climate system.

201. Youth Plaintiffs who live in Colorado are also adversely impacted by the opening up of an international market for the export of natural gas being extracted through hydraulic fracturing in the State of Colorado, and in the Rocky Mountain region of the U.S. generally, and then shipped by pipeline to Oregon for liquefaction and export abroad, ultimately to be burned, thereby causing additional CO_2 emissions. The Youth Plaintiffs from Colorado and Oregon are harmed by the fossil fuel exploitation in and running through their states, which will be

connected by the Pacific Connector Natural Gas Pipeline and 3,900 mile gas transmission system crossing the states of Washington, Oregon, Idaho, Wyoming, Utah, and Colorado.

IV. CURRENT SCIENCE ON GLOBAL CLIMATE CHANGE AND OCEAN ACIDIFICATION

202. There is a scientific consensus that climate change endangers humanity and nature. Present climate change is a consequence of anthropogenic GHGs, primarily CO_2, derived from the combustion of fossil fuels. The fossil fuel emissions have led to an energy imbalance and consequent dangerous disruption of the climate system upon which our nation and Plaintiffs depend.

203. Atmospheric CO_2 levels greater than 350 ppm cause this energy imbalance. That energy imbalance is now approximately 0.6 Watts/m2 averaged over the entire planet, equivalent to exploding more than 400,000 Hiroshima atomic bombs per day, 365 days per year, throughout our planet.

204. The 2014 National Climate Assessment acknowledged that "[t]he cumulative weight of the scientific evidence . . . confirms that climate change is affecting the American people now, and that choices we make will affect our future and that of future generations."

205. Greenhouse gases in the atmosphere act like a blanket over the Earth, trapping energy received from the sun. More GHG emissions in the atmosphere means that more energy is retained on Earth, with less being radiated back into space.

206. A substantial portion of every ton of CO_2 emitted by humans persists in the atmosphere for as long as a millennium or more. Therefore, the impacts associated with past and current CO_2 emissions will be borne by our children and future generations. Our nation will continue to warm in response to concentrations of CO_2 from past emissions, as well as future emissions.

207. The current level of atmospheric CO_2 concentration caused by human-made climate change has already taken our country into the danger zone.

208. In 2013, the atmospheric CO_2 concentration exceeded 400 ppm for the first time in recorded history. The pre-industrial concentration was 280 ppm. Emissions must be rapidly and systematically reduced to well below the natural rate of draw-down into Earth's forests, soils, and crust in order to restore energy balance and avoid crossing tipping points that set in motion disastrous impacts to human civilization and nature.

209. March 2015 was the first month that the monthly global average concentration of CO_2 was 400 ppm for an entire month, reaching levels that have not been seen for about three million years. CO_2 concentrations have risen more than 120 ppm since pre-industrial times, with half of that rise occurring since 1980.

210. Earth has now warmed about 0.9°C above pre-industrial temperatures. That temperature is equivalent to the maximum temperatures of the Holocene era, the period of climate stability over the last 10,000 years that enabled human civilization to develop. Warming is expected to hit 1°C in 2015-16.

211. Civilization and the water sources, crops, foods, wildlife, marine life, and coastlines on which people depend have developed within a very narrow set of climatic conditions. It will be nearly impossible for Plaintiff to adapt to all of the current climate change impacts in the quick time-frame in which they will occur. The survival and well-being of Plaintiffs is significantly threatened by climate destabilization.

212. Declaring the United States' energy system to be unconstitutional would resolve the controversy between the parties. Defendants would abide by the decree and bring the energy system into constitutional compliance, thereby redressing a substantial cause of Youth Plaintiffs'

constitutional injuries and eliminating a source of their significant risk of sustaining worsening injuries. Any "[f]urther or proper relief" that may be granted based on the declaratory judgment, 22 U.S.C. § 2202, regarding Defendants' national energy system policies and practices would further aid in reducing the earth's energy imbalance, the severity of the Youth Plaintiffs' injuries, the severity of Defendants' disruption of the climate system, and the severity and pace of ocean acidification, within the lifetimes of Youth Plaintiffs.

V. Existing Impacts of Climate Change Across the Nation

213. Climate change is already damaging human and natural systems, causing loss of life and pressing species to extinction. Unless arrested by government action informed by science, climate change will impose increasingly severe impacts on our nation and others, potentially to the point of collapse.

214. Recent scientific reports, for example, warn of the disintegration of both the West Antarctic ice sheet and the East Antarctic ice sheet, causing multi-meter sea-level rise. Such will devastate coastal regions, including much of the eastern seaboard. Millions of Americans and trillions of dollars in property damage will result. The risk of this devastation approaches certainty, unless fossil fuel emissions are rapidly phased out. The recent studies more fully than prior studies account for the potential for non-linear ice sheet melting, which could raise the sea level by 10 feet (or more) by mid-century.

215. If carbon pollution is not quickly abated, there is near scientific certainty that humanity will suffer sea level rise of several meters, submerging much of the eastern seaboard of the U.S., including Florida, as well as other low lying areas of Europe, the Far-East, and the Indian sub-continent.

216. Well-documented and observable impacts from the changes in Earth's climate system highlight that the current level of atmospheric CO_2 concentration has already taken our nation into a danger zone. Increased CO_2 emissions are already resulting not only in the warming of land surfaces, but also in the warming of oceans, increasing atmospheric moisture levels, rising global sea levels, and changing rainfall and atmospheric air circulation patterns that affect water and heat distribution.

217. One key observable change is the rapid increase in recorded surface temperatures. As a result of increased atmospheric CO_2 from human activities, our nation has been warming as scientists predicted as early as 1965. The increased concentrations of greenhouse gases in our atmosphere have raised global surface temperature by approximately 0.9° Celsius. In the last thirty years, Earth has been warming at a rate three times faster than that over the previous one hundred years. 2014 was the hottest on record, according to the National Aeronautics and Space Administration ("NASA").

218. As expected, our country's sea levels have also risen from glacial and ice cap melting, as well as from the thermal expansion of the ocean itself. Based on measurements taken from 1993 to 2010, sea levels have been rising at an average rate of 3.2 millimeters per year. Though sea levels rose about 170.18 millimeters (0.2 meters) over the last century, within the last decade, the rate of sea-level rise has nearly doubled. Rising seas have caused and will cause flooding in coastal and low-lying areas. The combination of rising sea levels and more severe storms creates conditions conducive to severe storm surges during high tides. In coastal communities this can overwhelm levees and sea walls, as witnessed during Hurricane Katrina, Hurricane Sandy, and other major storms.

219. Today, rising sea levels are submerging low-lying lands, eroding beaches, converting wetlands to open water, exacerbating coastal flooding, and increasing the salinity of estuaries and freshwater aquifers. Between 1996 and 2011, twenty square miles of land were inundated by rising sea levels along the Atlantic coast. Coastal states, such as Maryland and Louisiana, are experiencing wetland loss due to rising sea levels. Scientists have predicted that wetlands in the mid-Atlantic region of the U.S. cannot withstand a seven-millimeter per year rise in sea levels.

220. Similarly, climate change is already causing, and will continue to result in, more frequent, extreme, and costly weather events, such as floods and hurricanes. The annual number of major tropical storms and hurricanes has increased over the past 100 years in North America, coinciding with increasing temperatures in the Atlantic sea surface. Across the U.S., nine of the top ten years for extreme one-day precipitation events have occurred since 1990.

221. Changes in our country's water cycle as a result of climate change also increase the potential for, and severity of, droughts. Even in arid regions, increased precipitation is likely to cause flash flooding, and will be followed by drought. These changes are already occurring. Droughts in parts of the Midwestern, Southeastern, and Southwestern U.S. have increased in frequency and severity within the last fifty years, coinciding with rising temperatures. Most of the recent heat waves can be attributed to human-caused climate disruption.

222. In higher altitude and latitude regions, including in mountainous areas, more precipitation is falling as rain rather than snow. With early snow melt occurring because of climate change, the reduction in snowpack can aggravate water supply problems. The snow cover extent of North America in June 2015 was 0.75 million square miles, the second lowest ever recorded behind June 2012, with 0.68 million square miles. The average area of North

America covered by snow decreased by about 3,500 square miles per year between 1972 and 2013.

223. Arctic sea ice is declining precipitously and is expected to disappear completely in the coming decades. In 2013, Arctic sea ice extent for September was 700,000 square miles below the 1981-2010 average for the same period. In 2014, the Arctic sea ice extent for September was 463,000 square miles below average. In 2015, the maximum extent of the Arctic sea ice was the lowest in the satellite record. With less sea ice, less solar radiation is reflected back to space, a positive feedback loop serving to amplify regional and global warming.

224. Similarly, there has been an increase in permafrost temperatures and melting in Alaska. Substantial methane releases from thawing permafrost have already been observed in Alaska. Because much of the Alaskan permafrost overlays old peat bogs that sequester methane, permafrost melting ill release methane that will further increase global warming to even more dangerous levels. CO_2 and methane released from thawing permafrost could contribute as much as 0.4°F to 0.6°F of warming by 2100.

225. Mountain glaciers are receding nationwide because of warming temperatures. In 2010, Glacier National Park in Montana had only twenty-five glaciers larger than twenty-five acres, as opposed to 150 such glaciers in 1850. In the Brooks Range of northern Alaska, all of the glaciers are in retreat and in southeastern Alaska, 98% are in retreat.

226. The melting of mountain glaciers is particularly serious in areas that rely on snow melt for irrigation and drinking water supply. In effect, a large snow pack or glacier acts as a supplemental reservoir or water tower, holding a great deal of water in the form of ice and snow through the winter and spring and releasing it in the summer when rainfall is lower or absent. The water systems of the western U.S., particularly in California and Oregon, heavily rely on this

natural water storage. Yet as temperatures warm, not only will these areas lose this supplemental form of water storage, but severe flooding is also likely to increase as rainfall accelerates the melting of glaciers and snow packs.

227. Changes in water supply and water quality will also impact agriculture in the U.S. Increased heat and associated issues such as pests, crop diseases, and weather extremes, will all impact crop and livestock production and quality. For example, anthropogenic climate change in the U.S. has produced warmer summers, enabling the mountain pine beetle to produce two generations of beetles in a single summer season, where it had previously only been able to produce one. In Alaska, the spruce beetle is maturing in one year when it had previously taken two years. The expansion of the forest beetle population has killed millions of hectares of trees across the U.S. and resulted in millions of dollars lost from decreased tourism revenues.

228. Agriculture is extremely susceptible to climate change, threatening food security. Higher temperatures generally reduce yields of desirable crops while promoting pest and weed proliferation. Climate change is predicted to decrease crop yields, increase crop prices, decrease nationwide calorie availability, and increase malnutrition.

229. Increased wildfires, shifting precipitation patterns, higher temperatures, and drought conditions also threaten forest industries and private property. In the U.S., 72,000 wildfires have been recorded, on average, each year since 1983. Nine of the ten years with the largest acreage burned have occurred in the fourteen years since 2000.

230. Increased CO_2 emissions are having a severe negative impact on the health of our oceans. The oceans absorb approximately 25-30% of global CO_2 emissions, resulting in a 30% increase in surface ocean acidity.

231. Ocean acidification has been rising at a geologically unprecedented rate. Currently, acidity is rising at least 100 times faster than at any other period during the last 100,000 years, threatening marine life, including human food sources. Organisms at risk include: corals, oysters, clams, scallops, mussels, abalone, crabs, geoducks, barnacles, sea urchins, sand dollars, sea stars, sea cucumbers, many common single-celled organisms and protists that act as prey, and various forms of seaweed. The loss of some of these species can cause entire food webs to collapse.

232. By 2100, the surface waters of the ocean could be nearly 150% more acidic, resulting in a pH that the oceans have not experienced for more than 20 million years. In recent years, ocean acidification has already contributed to oyster reproductive failures impacting the Pacific Northwest's shellfish industry, including oyster harvests in Coos Bay, Oregon. In addition, warmer water in regional estuaries, such as Puget Sound, may contribute to a higher incidence of harmful blooms of algae linked to paralytic shellfish poisoning and may result in adverse economic impacts from beach closures affecting recreational harvesting of shellfish, such as razor clams.

233. The rise in ocean acidity places coral reefs at considerable risk. Given that coral reefs are among the most biologically diverse and economically important ecosystems, the impact of their loss cannot be overstated. Coral reefs provide shelter to a quarter of all marine species.

234. For major U.S. coral reefs, projections show extensive bleaching and dramatic loss of shallow coral cover occurring by 2050, and near complete loss by 2100. In Hawai‘i, coral cover is projected to decline from 38% (current coral cover) to approximately 5% by 2050, with further declines thereafter. In Florida and Puerto Rico, where present-day temperatures are

already close to bleaching thresholds, coral is projected to disappear even faster. Given the severity of these impacts, it is inevitable that these effects would be felt across our country, and by future generations.

235. Climate change and ocean acidification are threatening the survival and wellbeing of plants, fish, wildlife, and biodiversity. As many as one in six species are threatened with extinction due to climate change. Many more species that do not face extinction will face changes in abundance, distributions, and species interactions that cause adverse impacts for ecosystems and humans.

236. Salmon have historically been associated with human society and been a major contributor to the economy. Due to physical changes to freshwater ecosystems resulting from climate change, salmon populations have declined significantly across the country. The optimum water temperature for salmonids is 55° to 64° Fahrenheit; massive fish kills have occurred at or above 71° Fahrenheit. As of 2015, four salmon species in eighteen locations are on NOAA's Endangered and Threatened Marine Species list; in five locales they are extinct. Scientists from the Salmon 2100 Project, housed in an EPA research laboratory in Oregon, have predicted that, despite current recovery efforts, salmon runs are not likely to sustain themselves through 2100 and other recovery strategies must be adopted to combat climatic shifts.

237. Fossil fuel extraction and combustion, and the resulting climate change, is already contributing to an increase in allergies, asthma, cancer, cardiovascular disease, stroke, heat-related morbidity and mortality, food-borne diseases, injuries, toxic exposures, mental health and stress disorders, and neurological diseases and disorders. Climate change threatens the basic requirements for maintaining health like clean air, pure water, sufficient food, and adequate shelter. It also increases occurrence of infectious diseases.

238. In the U.S., 8,000 Americans have died from heat-related illnesses over the last three decades. There are now twice as many Lyme disease cases than were reported in 1991. In the past three decades, the percentage of Americans with asthma has more than doubled, and climate change is putting those Americans at greater risk of requiring hospitalization. Longer growing seasons allow for ragweed to produce pollen for a longer period, resulting in aggravated and prolonged allergies for millions of Americans.

239. Climate change also harms our national security, adding tension even in stable regions of the world. The DOD acknowledged the severity of climate change and its connections to national security when, in its 2014 Quadrennial Defense Review, climate change was classified as a "threat multiplier": "Pentagon leaders have identified three main ways that climate change will affect security; accelerating instability in parts of the world wracked by drought, famine, and climate-related migrations; threatening U.S. military bases in arid Western states or on vulnerable coastlines; and increasing the need for U.S. forces to respond to major humanitarian disasters."

240. By 2025, 40% of the world's population will be living in countries experiencing significant water shortages, while sea-level rise could cause displacement of tens, or even hundreds, of millions of people. As a result, the U.S. will experience an additional need to accept immigrant and refugee populations as droughts increase and food production declines in other countries. Increased extreme weather events (such as hurricanes) will also present an increased strain on foreign aid provided by the U.S. and materially increased deployment of our country's military forces.

241. Our nation is already observing significant impacts from the relatively small amount of warming that has occurred. These impacts constitute harbingers of far more

dangerous changes to come. If unabated, continued GHG emissions, especially CO_2, will initiate dynamic climate change and effects that spin out of control for Plaintiffs and future generations as the planet's energy imbalance triggers amplifying feedbacks and the climate system and biological system pass critical tipping points. Such changes would be irreversible on any time scale relevant to Plaintiffs and threaten their survival.

VI. FUTURE NATIONAL CLIMATE IMPACTS EXPECTED BY 2050 AND 2100

242. By 2050, Youth Plaintiffs will range in age from 43 to 55.

243. By 2100, global mean sea level rise is projected to be at 56 inches, if sea level rise occurs linearly. Based on that global projection, it is predicted that the U.S. will experience a 56-65 inch sea level rise on the East Coast, up to a 76-87 inch sea level rise in areas surrounding the Gulf of Mexico, and a 47-65 inch sea level rise along the West Coast. Sea level rise could be even more catastrophic depending upon the rate of disintegration of the Antarctic ice sheets. Sea level rise will result in increased erosion and the loss of land. In Washington and Oregon, more than 140,000 acres of coastal lands lie within 40 inches in elevation of high tide. Among the most vulnerable parts of the coast is the heavily populated south Puget Sound region, which includes Olympia, Tacoma, and Seattle, Washington.

244. New scientific evidence demonstrates that a non-linear process could trigger much greater sea level rise in a time frame of 50 to 200 years.

245. Global temperature increases are projected to increase by 9° Fahrenheit by 2100. In the U.S., the largest temperature increases are expected in the Mountain West and Northern regions consisting of 14° and 12° Fahrenheit, respectively.

246. In an EPA-funded study, "Ensemble Projections of Wildfire Activity and Carbonaceous Aerosol Concentrations Over the Western United States in the Mid-21st Century,"

scientists estimated that, by 2050, wildfire activity is expected to double in the Southwest, Pacific Northwest, Rocky Mountains Forest, and the Eastern Rockies/Great Plains regions. In the western U.S., increases in temperature are projected to cause an increase of 54% in annual mean area burned by 2050 relative to the present day. Changes in area burned are ecosystem dependent, with the forests of the Pacific Northwest and Rocky Mountains experiencing the greatest increases of 78% and 175%, respectively. Increased area burned results in near doubling of wildfire carbonaceous aerosol emissions by midcentury. The increase in wildfires and the associated emissions will have harmful impacts on health. Polar bears are just one of the species listed as endangered due to the impacts of a changing climate on their habitat. If emissions continue to rise at current rates throughout the 21st century, polar bears will likely be extirpated from much of their present-day range, including Alaska's North Slope Borough. Sea ice, which polar bears depend upon to access their prey, is projected to disappear by 2100. Experts project there will be massive species extinction this century.

247. Human-induced warming, if business continues as usual, is projected to raise average temperatures by about 6° to 11° Fahrenheit in this century. Heat waves would then increase in frequency, severity, and duration. For example, by the end of this century, if Defendants do not dramatically reduce emissions, the number of heat-wave days in Los Angeles is projected to double, and the number of heat-wave days in Chicago to quadruple, resulting in many more deaths.

248. While potential climate change impacts on water resources vary between regions, the western states will be particularly impacted by drought, reduced precipitation, increased evaporation, and increased water loss from plants.

249. Warmer temperatures particularly impact the Pacific Northwest because reduced snowpack and earlier snowmelt alter the timing and amount of water supplies. By 2050, snowmelt is projected to shift three to four weeks earlier than the 20th century average. Since earlier snowmelt will result in warmer and shallower rivers and streams in summer and fall, diseases and parasites that tend to flourish in warmer water threaten to eliminate up to 40% of remaining Northwest salmon populations by 2050.

250. By 2050, biologists conservatively expect decreases in salmon populations will lead to 11% to 14% less annual carcass biomass available to bald eagles, our country's national bird.

251. Defendants, through the Department of Homeland Security, have acknowledged mass human migrations are a potential impact of climate change, and have developed a mass migration plan. Estimates put the number of climate-induced migrants worldwide at 200 million by 2050.

252. Climate change projections estimate an increase in monetary damages associated with inland flooding across most of the contiguous U.S. Approximately 190,000 of our nation's bridges are vulnerable to increased inland flooding caused by climate change, with adaptation costs estimated at $170 billion for the period from 2010 to 2050. In the Northwest, a region including Washington and parts of Oregon and Idaho, 56% of inland bridges are identified as vulnerable in the second half of the 21st Century.

253. In 2100 alone, adaptation costs associated with the 50-year, 24-hour storm moniker in 50 U.S. cities are estimated to range from $1.1 to $12 billion. Further, climate change is projected to result in $5.0 trillion in damage to coastal properties in the contiguous U.S. through 2100.

254. Due to extreme temperature increases and unsuitable working conditions, our nation's labor force may experience a drastic decline in labor hours and lost wages. In 2100, a projected 1.8 billion labor hours will be lost along with approximately $170 billion in lost wages.

255. By 2050, climate change is expected to add thousands of additional premature deaths per year nationally from combined ozone and particle health effects. Higher surface temperatures, especially in urban areas, promote the formation of ground–level ozone, which has adverse impacts on human health by irritating the respiratory system, reducing lung function, aggravating asthma, and inflaming and damaging cells that line the airways. Climate change is expected to increase the frequency of high ozone pollution events by 50% to 100% by 2050.

VII. RESTORING THE ENERGY BALANCE AND PROTECTING AGAINST A DANGEROUS DESTABILIZED CLIMATE SYSTEM IS POSSIBLE BASED ON BEST AVAILABLE SCIENCE

256. An urgent and critical undertaking is required to protect the climate system and cause a cessation of Defendants' infringement of Plaintiffs' constitutional rights. Defendants must act rapidly and effectively to phase out CO_2 emissions so as to restore Earth's energy balance. Absent such immediate action, the Federal Government must cease permitting and authorizing fossil fuel projects so as not to exacerbate the climate crisis and further infringe on Plaintiffs' constitutional rights.

257. Global atmospheric CO_2 concentrations must be reduced to below 350 ppm by the end of the century in order to limit the period of CO_2 overshoot and stabilize our climate system.

258. To reduce global atmospheric CO_2 concentrations to 350 ppm by the end of this century would require a near-term peak in CO_2 emissions and a global reduction in CO_2 emissions of at least 6% per year, alongside approximately 100 gigatons of carbon drawdown this century from global reforestation and improved agriculture.

259. Reducing the global atmospheric CO_2 concentration to 350 ppm by the end of the century is also necessary in order to protect oceans and marine life. As a result of CO_2 emissions, of which approximately 25% are absorbed by the oceans, humans, marine organisms, and ecosystems are already harmed and will increasingly be harmed by ocean acidification. To prevent the further impairment or depletion of the oceans and oceanic resources, it is imperative that Defendants take immediate measures to return atmospheric CO_2 concentrations to below 350 ppm by the end of this century.

260. Targets that aim to limit atmospheric CO_2 concentrations at or below 450 ppm are insufficient to avoid severe, irreversible damage as a result of ocean acidification and ocean warming. For example, the weight of recent evidence establishes that, at a prolonged 450 ppm level, coral reefs will become extremely rare, if not extinct, and at least half of coral-associated wildlife will become either rare or extinct. As a result, coral reef ecosystems will likely be reduced to crumbling frameworks with few calcareous corals remaining.

261. Current actions by Defendants will not yield atmospheric CO_2 levels of 350 ppm by the end of the century, are not based on any scientific standard, and are not adequate to prevent and remedy the degradation, diminution, or depletion of our country's public trust resources.

262. Defendants' national energy system makes it extremely difficult for Plaintiffs to protect their vital natural systems and a livable world. Defendants must act immediately to restore Earth's energy balance and put the nation on a trajectory that is consistent with reducing the atmospheric CO_2 concentrations to no more than 350 ppm by <u>2100</u>.

VIII. THE FEDERAL GOVERNMENT'S ADMISSIONS OF ITS PUBLIC TRUSTEE OBLIGATIONS

263. Defendants are trustees of national public natural resources. The national public natural resources include the air (atmosphere), seas, shores of the sea, water, and wildlife.

264. In 1968, Congress declared that the Federal Government has "continuing responsibility" to "use all practicable means" so as to "fulfill the responsibilities of each generation as trustee of the environment for succeeding generations." 42 U.S.C. § 4331(b)(1).

265. Congress also declared that the Federal Government is among the "trustees for natural resources" and directed Defendants to act as trustees, on behalf of the public beneficiaries, of all natural resources under their management and control. 42 U.S.C. § 9607 (f)(1); *see also* 33 U.S.C. § 2706 (Oil Pollution Act).

266. Pursuant to Congressional direction, the President designated the following federal agencies to act on behalf of the public as trustees for natural resources: the USDA, Commerce, DOD, DOE, and DOI. In this context, the term natural resources "means land, fish, wildlife, biota, air, water, ground water, drinking water supplies, and other such resources belonging to, managed by, held in trust by, appertaining to, or otherwise controlled (referred to as 'managed or controlled') by the United States (including the resources of the exclusive economic zone)." 40 C.F.R. § 300.600(a); *see* 42 U.S.C. § 9607 (f)(2)(A).

267. According to the National Research Council, "fisheries within federal waters are held in public trust for the people of the United States."

268. According to the U.S. Commission on Ocean Policy, "the U.S. government holds ocean and coastal resources in the public trust – a special responsibility that necessitates balancing different uses of those resources for the continued benefit of all Americans."

269. According to NOAA, it "has an obligation to conserve, protect, and manage living marine resources in a way that ensures their continuation as functioning components of marine ecosystems, affords economic opportunities, and enhances the quality of life for the American public." Further, NOAA affirmed that air is a natural resource under the public trust doctrine, and that the Federal Government shares jurisdiction with states over such public trust resources.

270. NOAA admits that one principle of the public trust doctrine is: "The public has fundamental rights and interests in natural resources such as the sea, the shore, and the air."

271. The DOI admits that the public trust doctrine "now encompasses all natural resources," and that natural resources include "land, fish, wildlife, biota, air, water, ground water, drinking water supplies and other such resources belonging to, managed by, held in trust by, appertaining to, or otherwise controlled by the U.S." The DOI admits that the "Department of the Interior, Department of Commerce (delegated to NOAA), Department of Energy, Department of Agriculture, Department of Defense, and any other Federal Land Managing Agency" are "Federal Trustees."

272. The State Department admitted "an obligation to current and future generations to take action" on climate change.

273. The United States has taken the position before federal courts that the Federal Government is a trustee over important national natural resources, including wildlife, and has both rights and obligations under the public trust doctrine.

274. By way of example, in a 2010 complaint filed against British Petroleum, the United States alleged: "Natural resources under the trusteeship of the United States and other sovereigns have been injured, destroyed, or lost as a result of discharged oil and associated

removal efforts. The discharged oil is harmful to natural resources exposed to the oil, including aquatic organisms, birds, wildlife, vegetation, and habitats."

275. Since 1965, Defendants have known they each have mandatory duties to abate CO_2 pollution from fossil fuels in order to stop global climate change: "The pervasive nature of pollution, its disregard of political boundaries including state lines, the national character of the technical, economic and political problems involved, and the recognized Federal responsibilities for administering vast public lands which can be changed by pollution, for carrying out large enterprises which can produce pollutants, for preserving and improving the nation's natural resources, all make it mandatory that the Federal Government assume leadership and exert its influence in pollution abatement on a national scale."

276. Defendants have exerted their influence, control, custodianship, and sovereignty over the polluted atmosphere and the exploitation of fossil fuels, but they have not abated the harm. Because Defendants have put Plaintiffs in danger and increased Plaintiffs' susceptibility to harm, Defendants are responsible for taking action to protect Plaintiffs. In fact, Defendants have exacerbated the harm to our atmosphere in violation of Plaintiffs' constitutional rights.

276-A. This Court should issue a declaratory judgment to resolve this actual constitutional case and controversy between these young Plaintiffs and the government Defendants as to whether Defendants' national energy system has violated and continues to violate Plaintiffs' constitutional rights as described herein. Until the Court resolves this constitutional controversy, these young Plaintiffs will continue to be harmed and put at extreme risk by Defendants' energy system and Defendants will continue policies and practice, made up of many aggregate actions, to perpetuate an unconstitutional energy system, avoiding the constitutional check of Article III courts, and undermining the separation of powers that the

Framers intended. Without declaratory relief in the first instance, Defendants will be free to, and will, continue its policies and practices that make the nation's energy system in a manner that "may hasten an environmental apocalypse" and carry out "the Nation's willful destruction." Declaratory judgment will eliminate the current and substantial legal controversy and inform the parties of the unlawfulness or lawfulness of the government's conduct, especially as to whether Defendants' conduct causes a deprivation of rights secured by the Constitution. It has long been held that there is an expectation in our democracy that government officials will comply with a declaratory judgment. *Utah v. Evans*, 536 U.S. 452, 463-64 (2002). If the constitutional controversy is resolved in their favor by declaratory judgment, Plaintiffs reserve the right to seek further relief as deemed appropriate and consistent with the separation of powers between the three branches of government. Plaintiffs come before this Court to defend and secure their fundamental rights under the Constitution, before it is too late.

CLAIMS FOR RELIEF

First Claim for Relief
Violation of the Due Process Clause of the Fifth Amendment

277. Plaintiffs hereby re-allege and incorporate by reference each of the allegations set forth above.

278. The Constitution recognizes and preserves the fundamental right of citizens to be free from government actions that harm life, liberty, and property. These inherent and inalienable rights reflect the basic societal contract of the Constitution to protect citizens and posterity from government infringement upon basic freedoms and basic (or natural) rights. The rights to life, liberty, and property have evolved and continue to evolve as technological advances pose new threats to these fundamental rights and as new insights reveal discord between the Constitution's central protections and the conduct of government. As set forth in the

Preamble of the Constitution, these rights belong to present generations as well to our "Posterity" (or future generations).

279. Our nation's climate system, including the atmosphere and oceans, is critical to Plaintiffs' rights to life, liberty, and property. Our nation's climate system has been, and continues to be, harmed by Defendants. Defendants harmed our nation's climate system with full appreciation of the results of their acts. Plaintiffs' substantive Fifth Amendment rights have been infringed because Defendants' national energy system is a substantial factor in causing atmospheric CO_2 to rise to levels that dangerously interfere with a stable climate system required alike by our nation and Plaintiffs. The present CO_2 concentration and continuing CO_2 emissions – a function, in substantial part, of Defendants' historic and continuing permitting, authorizing, and subsidizing of fossil fuel extraction, production, transportation, and utilization – endangers Plaintiffs' lives, liberties, and property.

280. For the past fifty years, Defendants have known about the danger to Plaintiffs' safety created by carbon pollution. Acting with full appreciation of the consequences of their acts, Defendants knowingly caused, and continue to cause, dangerous interference with our atmosphere and climate system. Defendants have knowingly endangered Plaintiffs' health and welfare by approving and promoting fossil fuel development, including exploration, extraction, production, transportation, importation, exportation, and combustion, and by subsidizing and promoting this fossil fuel exploitation. All of these deliberate actions by Defendants have cumulatively resulted in dangerous levels of atmospheric CO_2, which deprive Plaintiffs of their fundamental rights to life, liberty, and property.

281. Plaintiffs are suffering harm by the dangerous aggregate actions and deliberate omissions of Defendants. Defendants' dangerous interference with a stable climate system is

having such irreversible and catastrophic consequences as to shock the conscience. The conduct, if not fundamentally altered, will have even worse consequences for future generations.

282. The affirmative aggregate acts of Defendants have been and are infringing on Plaintiffs' right to life by causing dangerous CO_2 concentrations in our nation's atmosphere and dangerous interference with our country's stable climate system.

283. The affirmative aggregate acts of Defendants have been and are infringing on Plaintiffs' liberties by placing Plaintiffs in a position of danger with a destabilized climate system and dangerous levels of CO_2 in our country's atmosphere. Defendants' aggregate acts of increasing CO_2 concentrations in the atmosphere have been and are harming Plaintiffs' dignity, including their capacity to provide for their basic human needs, safely raise families, practice their religious and spiritual beliefs, maintain their bodily integrity, and lead lives with access to clean air, water, shelter, and food.

284. After knowingly creating this dangerous situation for Plaintiffs, Defendants continue to knowingly enhance that danger by allowing fossil fuel production, consumption, and combustion at dangerous levels, thereby violating Plaintiffs' substantive Fifth Amendment due process rights.

285. After placing Plaintiffs in a position of climate danger, Defendants have continued to act with deliberate indifference to the known danger they helped create and enhance. A destabilized climate system poses unusually serious risks of harm to Plaintiffs' lives and their bodily integrity and dignity. As described at length, *supra*, these risks are so substantial as to shock the conscience. Defendants have had longstanding, actual knowledge of the serious risks of harm and have failed to take necessary steps to address and ameliorate the known, serious risk to which they have exposed Plaintiffs. With deliberate indifference,

Defendants have not implemented their own plans for climate stabilization or any other comprehensive policy measures to effectively reduce CO_2 emissions to levels that would adequately protect Plaintiffs from the dangerous situation of climate destabilization.

286. By exercising sovereignty over the air space, the federal public domain, and the national energy system, by assuming authority and regulatory responsibility over fossil fuels, and by allowing and permitting fossil fuel production, consumption, and its associated CO_2 pollution, Defendants have also assumed custodial responsibilities over the climate system within its jurisdiction and influence. In assuming control of our nation's atmosphere, air space, the federal domain, national energy system, fossil fuels, and climate system, Defendants have imposed severe limitations on Plaintiffs' freedom to act on their own behalf to secure a stable climate system and, therefore, have a special relationship with Plaintiffs, and a concomitant duty of care to ensure their reasonable safety. By and through the national energy system resulting in dangerous interference with a stable climate system, Defendants have abrogated their duty of care to protect Plaintiffs' fundamental rights to life, liberty, and property. In their custodial role, Defendants have failed to protect Plaintiffs' needs with respect to the climate system in violation of the Fifth Amendment.

287. Furthermore, Defendants' national energy system, if not fundamentally altered without delay, will effect a complete taking of some of Plaintiffs' property interests by virtue of the sea level rise that is an incident of Defendants' unlawful actions.

288. The United States, through DOE, is depriving Plaintiffs of their fundamental rights to be free from the dangerous government acts, which infringe on their fundamental rights to life, liberty, and property, by requiring and giving approval for the exportation and importation of natural gas resources in the U.S. through section 201 of the Energy Policy Act of

1992. The extraction, interstate transport, liquefaction, exportation, and ultimate combustion of U.S. natural gas, facilitated by section 201 of the Energy Policy Act, increase carbon pollution and exacerbate already-dangerous climate instability. Section 201 of the Energy Policy Act is unconstitutional on its face and as applied to Plaintiffs through DOE's issuance of the section 201 permit for Jordan Cove LNG Terminal in Coos Bay, Oregon. The Energy Policy Act and DOE's actions taken pursuant to the Energy Policy Act deprive Plaintiffs of their fundamental rights to life, liberty, and property.

289. The affirmative aggregate acts of Defendants in the areas of fossil fuel extraction, production, transportation, importation and exportation, and consumption, as described in this Complaint, are causing dangerous concentrations of CO_2 in the atmosphere and a dangerous climate system, and irreversible harm to the natural systems critical to Plaintiffs' rights to life, liberty, and property. The affirmative aggregate acts of Defendants cannot and do not operate to secure a more compelling state interest than Plaintiffs' fundamental rights to life, liberty, and property.

WHEREFORE, Plaintiffs pray for relief as more fully set forth below.

Second Claim for Relief
Violation of Equal Protection Principles
Embedded in the Fifth Amendment

290. Plaintiffs hereby re-allege and incorporate by reference each of the allegations set forth above.

291. Defendants have violated the equal protection principles of the Fourteenth Amendment, embedded in the Due Process Clause of the Fifth Amendment.

292. The affirmative aggregate acts of Defendants in the areas of fossil fuel production and consumption irreversibly discriminate against Plaintiffs' exercise of their fundamental rights

to life, liberty, and property, and abridge central precepts of equality. The affirmative aggregate acts of Defendants in the areas of fossil fuel production and consumption have caused and are causing irreversible climate change. As a result, the harm caused by Defendants has denied Plaintiffs the same protection of fundamental rights afforded to prior and present generations of adult citizens. The imposition of this disability on Plaintiffs serves only to disrespect and subordinate them. The principles of the Equal Protection Clause, which are embedded in the Due Process Clause, prohibit the Federal Government's unjustified infringement of Plaintiffs' right to be free from Defendants' aggregate acts that destabilize our nation's climate system whose protection is fundamental to Plaintiffs' fundamental rights to life, liberty, and property. Because fundamental rights are at stake and are being infringed by the affirmative aggregate acts of Defendants, this Court must apply strict scrutiny for a denial of equal protection of the law.

293. The Fifth Amendment's Due Process Clause and the Fifth Amendment's equal protection principles are profoundly connected but set forth distinct principles, which are implicated here. The reason why a stable climate system is inherent in our fundamental rights to life, liberty, and property becomes more clear and compelling because of the grave and continuing harm to children that results from discriminatory laws and actions that prevent a stable climate system. The application of these dual principles requires strict scrutiny of Defendants' discriminatory laws and actions.

294. Plaintiffs are separate suspect classes in need of extraordinary protection from the political process pursuant to the principles of Equal Protection. As evidenced by their affirmative aggregate acts, Defendants have a long history of deliberately discriminating against children and future generations in exerting their sovereign authority over our nation's air space and federal fossil fuel resources for the economic benefit of present generations of adults.

Plaintiffs are an insular minority with no voting rights and little, if any, political power or influence over Defendants and their actions concerning fossil fuels. Plaintiffs have immutable age characteristics that they cannot change.

295. Future generations do not have present political power or influence, have immutable characteristics, and are also an insular minority.

296. Plaintiffs have no avenues of redress other than this Court, as Plaintiffs cannot challenge or alter Defendants' national energy system. Plaintiffs will disproportionately experience the irreversible and catastrophic impacts of an atmosphere and oceans containing dangerous levels of CO_2 and a dangerous destabilized national climate system. The adults living in our country today will not experience the full scope of catastrophic harms that will be experienced by Plaintiffs.

297. For purposes of the present action, Plaintiffs should be treated as protected classes because the overwhelming majority of harmful effects caused by the acts of Defendants will occur in the future. As Plaintiffs include citizens presently below the voting age and future generations, this Court should determine they must be treated as protected classes, and federal laws and actions that disproportionately discriminate against and endanger them must be invalidated.

298. The affirmative aggregate acts of Defendants reflect a *de facto* policy choice to favor influential and entrenched short-term fossil fuel energy interests to the long-term detriment of Plaintiff—precisely the sort of dysfunctional majoritarian outcome that our constitutional democratic system is designed to check. Such a check is especially appropriate here because our country will soon pass the point where Plaintiffs will no longer be able to secure equal protection of the laws and protection against an uninhabitable climate system.

299. The Energy Policy Act's mandatory authorization for export and import of natural gas discriminates against Plaintiffs by exacerbating already-dangerous levels of atmospheric CO_2 and a dangerous climate system, the consequences of which will be irreversible and catastrophic in Plaintiffs' lifetimes. The Energy Policy Act, section 201, creates a disproportionate impact on suspect classes. Historical evidence demonstrates Defendants' discriminatory and intentional acts against children and future generations in order to foster the short-term economic and energy interests of other classes, including corporations. The Energy Policy Act unconstitutionally deprives minor children and future generations of equal protection of the law because the full impacts of excess atmospheric CO_2 and the dangerous climate system, resulting from the U.S. government-authorized natural gas exports and imports, will be disproportionately imposed upon minor children, including Youth Plaintiffs, and for millennia by future generations.

300. Section 201 of the Energy Policy Act violates Plaintiffs' rights of equal protection under the law.

301. The affirmative aggregate acts of Defendants unconstitutionally favor the present, temporary economic benefits of certain citizens, especially corporations, over Plaintiffs' rights to life, liberty, and property.

WHEREFORE, Plaintiffs pray for relief as more fully set forth below.

Third Claim for Relief
The Unenumerated Rights Preserved for the People by the Ninth Amendment

302. Plaintiffs hereby re-allege and incorporate by reference each of the allegations set forth above.

303. Protecting the vital natural systems of our nation for present and future generations is fundamental to our scheme of ordered liberty and is deeply rooted in this nation's

history and tradition. Without a stable climate system, both liberty and justice are in peril. Our nation's obligation to protect vital natural systems for Posterity has been recognized throughout American history, particularly through our country's conservation legislation. Our nation's founders intended that the federal government would have both the authority and the responsibility to be a steward of our country's essential natural resources. This stewardship is clear from the delegation of powers to manage lands and the conveyed authority to address major challenges facing our nation as a whole. Among the implicit liberties protected from government intrusion by the Ninth Amendment is the right to be sustained by our country's vital natural systems, including our climate system.

304. Fundamental to our scheme of ordered liberty, therefore, is the implied right to a stable climate system and an atmosphere and oceans that are free from dangerous levels of anthropogenic CO_2. Plaintiffs hold these inherent, inalienable, natural, and fundamental rights.

305. The affirmative aggregate acts of Defendants have unconstitutionally caused, and continue to materially contribute to, dangerous levels of atmospheric and oceanic CO_2 and a destabilized climate system.

306. The affirmative aggregate acts of Defendants have infringed, and continue to infringe, on Plaintiffs' fundamental constitutional rights.

WHEREFORE, Plaintiffs pray for relief as more fully set forth below.

Fourth Claim for Relief
Violation of the Public Trust Doctrine

307. Plaintiffs hereby re-allege and incorporate by reference each of the allegations set forth above.

308. Plaintiffs are beneficiaries of rights under the public trust doctrine, rights that are secured by the Ninth Amendment and embodied in the reserved powers doctrines of the Tenth

Amendment and the Vesting, Nobility, and Posterity Clauses of the Constitution. These rights protect the rights of present and future generations to those essential natural resources that are of public concern to the citizens of our nation. These vital natural resources include at least the air (atmosphere), water, seas, the shores of the sea, and wildlife. The overarching public trust resource is our country's life-sustaining climate system, which encompasses our atmosphere, waters, oceans, and biosphere. Defendants must take affirmative steps to protect those trust resources.

309. As sovereign trustees, Defendants have a duty to refrain from "substantial impairment" of these essential natural resources. The affirmative aggregate acts of Defendants in the areas of fossil fuel production and consumption have unconstitutionally caused, and continue to cause, substantial impairment to the essential public trust resources. Defendants have failed in their duty of care to safeguard the interests of Plaintiffs as the present and future beneficiaries of the public trust. Such abdication of duty abrogates the ability of succeeding members of the Executive Branch and Congress to provide for the survival and welfare of our citizens and to promote the endurance of our nation.

310. As sovereign trustees, the affirmative aggregate acts of Defendants are unconstitutional and in contravention of their duty to hold the atmosphere and other public trust resources in trust. Instead, Defendants have alienated substantial portions of the atmosphere in favor of the interests of private parties so that these private parties can treat our nation's atmosphere as a dump for their carbon emissions. Defendants have failed in their duty of care as trustees to manage the atmosphere in the best interests of the present and future beneficiaries of the trust property, including, but not limited to, Plaintiffs. Such abdication of duty abrogates the

sovereign powers of succeeding members of the Executive Branch and Congress to provide for the survival and welfare of our Nation's citizens and to promote the endurance of our Nation.

PRAYER FOR RELIEF

WHEREFORE, Plaintiffs pray for relief as set forth below:

1. Pursuant to 28 U.S.C. § 2201 and this Court's Article III authority, enter a judgment declaring the United States' national energy system that creates the harmful conditions described herein has violated and continues to violate the Fifth Amendment of the U.S. Constitution and Plaintiffs' constitutional rights to substantive due process and equal protection of the law;
2. Pursuant to 28 U.S.C. § 2201 and this Court's Article III authority, enter a judgment declaring the United States' national energy system that creates the harmful conditions described herein has violated and continues to violate the public trust doctrine;
3. Pursuant to 28 U.S.C. § 2201 and this Court's Article III authority, enter a judgment declaring that § 201 of the Energy Policy Act has violated and continues to violate the Fifth Amendment of the U.S. Constitution and Plaintiffs' constitutional rights to substantive due process and equal protection of the law.
4. Pursuant to this Court's declaratory judgment, 28 U.S.C. § 2202, and this Court's Article III authority, if deemed necessary, just and proper, issue an appropriate injunction restraining Defendants from carrying out policies, practices, and affirmative actions that render the national energy system unconstitutional in a manner that harms Plaintiffs;

5. Award Plaintiffs their costs and reasonable attorneys' fees;

6. Pursuant to 28 U.S.C. § 2202 and this Court's Article III authority, grant such other and further relief as the Court deems just and proper, to redress the constitutional violations so declared.

Respectfully submitted this 9th day of March, 2021,

s/ Julia A. Olson

JULIA OLSON (OR Bar 062230)
julia@ourchildrenstrust.org
Our Children's Trust
1216 Lincoln Street
Eugene, OR 97401
Tel: (415) 786-4825

PHILIP L. GREGORY (*pro hac vice*)
pgregory@gregorylawgroup.com
Gregory Law Group
1250 Godetia Drive
Redwood City, CA 94062
Tel: (650) 278-2957

ANDREA K. RODGERS (OR Bar 041029)
andrea@ourchildrenstrust.org
Our Children's Trust
3026 NW Esplanade
Seattle, WA 98117
Tel: (206) 696-2851

Attorneys for Plaintiffs

Exhibit A

Declaration of Dr. James E. Hansen in Support of Plaintiffs' Complaint for Declaratory and Injunctive Relief

In the matter
Kelsey Cascadia Rose Juliana, Xiuhtezcatl Tonatiuh M. et al. v. United States, Barack Obama et al. (D. Or. Aug. 12, 2015)

I, DR. JAMES E. HANSEN, hereby declare as follows:

1. I make and offer this declaration in my capacity as guardian for Plaintiffs Sophie K. and Future Generations, and as an expert in the field of climate science.

2. I am Sophie's grandfather.

3. I am also a US citizen, an Adjunct Professor at Columbia University's Earth Institute, and Director of the Climate Science, Awareness and Solutions program at the Earth Institute, Columbia University. I am also the immediate past Director of the NASA Goddard Institute for Space Studies and a member of the United States National Academy of Sciences.

I have testified before the United States Senate and House of Representatives on many occasions, and in court on several occasions, in support of efforts to reduce reliance on carbon-intense energy from fossil fuels and rapidly transition to carbon-free energy.

4. My training is in physics and astronomy, with early research on the clouds of Venus. Since the late 1970s, I have focused my research on Earth's climate, especially human-made climate change. Most recently, I have dedicated significant effort towards outlining the actions that must be undertaken by communities, states, the U.S. Government, and others, in order to preserve a viable climate system for young people, future generations, and other life on Earth. For the Court's more complete reference, I have attached my full CV as **<u>Exhibit 1</u>** to this declaration.

5. In my opinion, this lawsuit is made necessary by the at-best schizophrenic, if not suicidal, nature of U.S. climate and energy policy.

6. On the one hand, our federal government has recognized a fundamental duty to protect the public resources of our nation; to safeguard our lives and property; to secure the blessings of liberty; to ensure equal protection under the law for "ourselves and our posterity";

and, pursuant to the United Nations Framework Convention on Climate Change (UNFCCC), to "protect the climate system for present and future generations."

7. On the other hand, the federal government continues to permit and otherwise support industry's efforts to exploit fully our reserves of gas, coal, and oil, even in the face of increasing overwhelming evidence that our continued fossil fuel dependency is driving the atmospheric concentration of carbon dioxide (CO_2) far beyond that in human experience, and constitutes one of the greatest threats to our nation, human civilization and nature alike.

8. These antinomies cannot be explained away as the product of ignorance. Our government has known for decades that the continued burning of coal, oil and natural gas causes global warming and risks dangerous and uncontrollable destabilization of the planet's climate system on which our nation and future generations depend.

9. Moreover, the government has, during this last half decade, promoted the exploitation and consumption of fossil fuels in myriad ways. They include: permitting of fossil fuel development projects within the U.S.; financing of overseas fossil fuel development projects through the Export Import Bank and World Bank; issuance of leases and permits for oil, gas and coal extraction and development on contiguous federal and OCS lands; and subsidies through tax credits, deductions, preferences, percentage depletion, expensing, favorable loans and guarantees, accelerated amortization, below fair-market-value lease and royalty requirements, and other favorable tax treatment for fossil fuel development. This listing is partial.

10. It is now clear, as the relevant scientific community has established for some time, that continued high CO_2 emissions from fossil fuel burning will further disrupt Earth's climate system, and that, in turn, will impose profound and mounting risks of ecological, economic and social collapse. In my view, our government's actions and inactions that cause or contribute to

those emissions violate the fundamental rights of Sophie, other Youth, and future generations. Those violated rights include the right to life, the right to liberty, the right to property, the right to equal protection under the law, the right to government protection of public trust resources, and the right to retain a fighting chance to preserve a habitable climate system.

11. Here, then, I will address the fundamental context in which those fundamental rights violations arise. That context includes Earth's present and growing energy imbalance and the still real, but highly time-limited, opportunity to rapidly phase-down CO_2 emissions, restore energy balance, and stabilize the climate system.

12. The Court will find a more detailed treatment of these points, with supporting explanatory material and data, in two recent papers of which I am the lead author.

13. The first, Assessing ''Dangerous Climate Change'': Required Reduction of Carbon Emissions to Protect Young People, Future Generations and Nature, was published in late 2013, in conjunction with 17 colleagues. In that study we established that continued fossil fuel burning up to even 2^{o}C above the preindustrial level[1] likely would cause large climate change with disastrous and irreversible consequences, so that actions to rapidly phase out CO_2 emissions are urgently needed to reduce the atmospheric CO_2 concentration to no more than 350ppm and restore Earth's energy balance. I have attached *Dangerous Climate Change* hereto as **Exhibit 2**,[2] and I hereby incorporate by reference, into this declaration, its analyses and conclusions.

[1] We are already 0.9^{o}C above the preindustrial temperature. Indeed, in 2015 global temperature is reaching a level ~1°C above the preindustrial level, but the high 2015 level is partly a temporary effect of a strong El Nino, a natural oscillation of tropical Pacific Ocean temperature.

[2] Published by PLOS One (Dec. 3, 2013) and available at: http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0081648

14. The second, Ice Melt, Sea Level Rise and Superstorms: Evidence from Paleoclimate Data, Climate Modeling, and Modern Observations that 2°C Global Warming is Highly Dangerous, was published this month in conjunction with 16 colleagues. In it we conclude that, if CO_2 emissions are allowed such that energy is continuously pumped at a high rate into the ocean, then multi-meter sea level rise will become practically unavoidable, with consequences that may threaten the very fabric of civilization. I have attached *Ice Melt, Sea Level Rise and Superstorms* hereto as **Exhibit 3**,[3] and hereby incorporate by reference into this declaration its analyses and conclusions.

I. PRESENT AND LOOMING CLIMATE CRISES, AND A PATH TO STABILITY

15. As indicated above, our late-2013 study provides a detailed treatment of our present predicament and the route that must be taken to sufficiently reduce atmospheric CO_2 to preserve a habitable climate system. *See* **Exhibit 2**. Our most recent work, establishing that nonlinear melting of Earth's major ice sheets is likely within a century, among other things, if fossil fuel emissions continue unabated, adds an additional element of immediacy to what, for too long, has been treated in practical terms as, at best, a distant but growing complication. *See* **Exhibit 3**.

16. I outline and summarize these matters here, before proceeding to a further explanation of them.

17. **First**: Human burning of fossil fuels has disrupted Earth's energy balance. In response, the planet is heating up – with no end in sight, unless we alter our present path. Atmospheric CO_2 concentration, for example, is now at its highest level in 3 million years, and

[3] *See also*: http://www.atmos-chem-phys-discuss.net/15/20059/2015/acpd-15-20059-2015.pdf

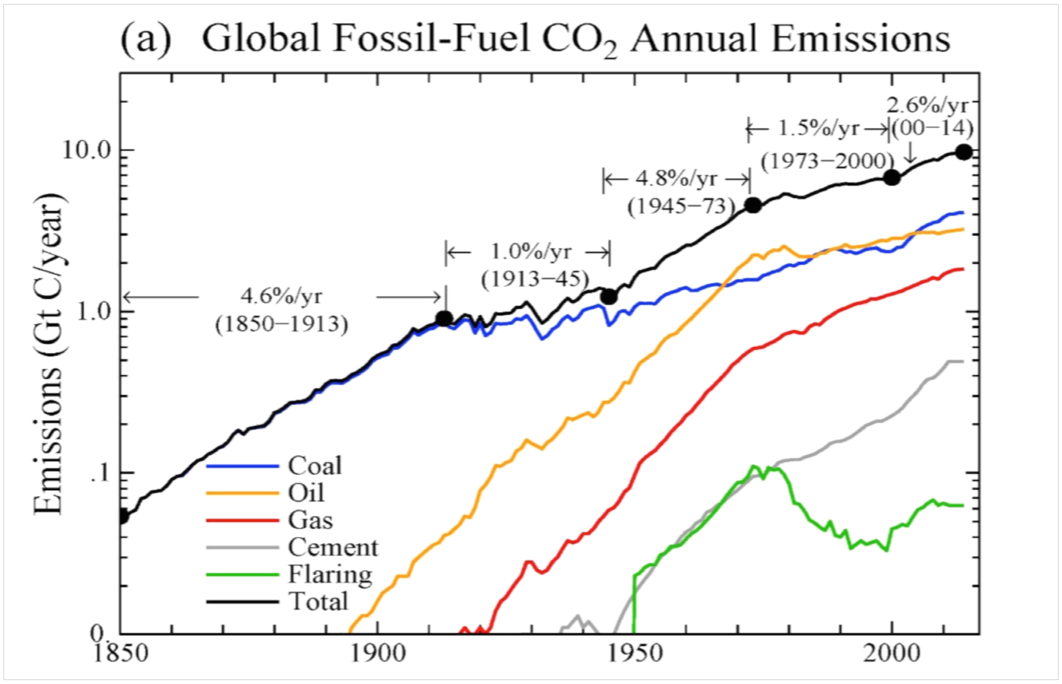
global surface temperatures now have reached the prior maximum of the Holocene era, the period of relatively moderate climate that, over the last 10,000 years, enabled civilization to develop.

18. **Second**: We are observing impacts of the relatively small amount of warming that has already occurred, and these constitute harbingers of far more dangerous change to come. We can discuss the observable consequences, and their implications, but the key point is that, if unabated, continued carbon emissions will initiate dynamic climate change and effects that spin out of human control, as the planet's energy imbalance triggers amplifying feedbacks and the climate and biological systems pass critical tipping points. Sea-level rise provides a key metric here.

19. **Third**: There is still time and opportunity to preserve a habitable climate system -- if we pursue a rational course. I will outline the glide path that we think remains feasible, though further delay in taking effective action will consign that effort to failure. Objectively, then, the situation is urgent and what governments and other decision-makers do, or do not do, today to reduce carbon pollution matters immensely.

II. OUR PLANET IS NOW OUT OF ENERGY BALANCE

20. In Chart 1, we show global fossil fuel CO_2 emissions on an annual basis from the burning of coal, oil, and natural gas, and from cement production and flaring, along with the total emissions from these major sources. Although it is more than twenty years since 170 nations agreed to limit fossil fuel emissions in order to avoid dangerous human-made climate change, the stark reality – as illustrated here – is that global emissions have accelerated. Specifically, the growth rate of fossil fuel emissions increased from 1.5%/year during 1973–2000 to 2.6%/year in 2000–2014 (Chart 1(a)), due in the main to increased utilization of coal, oil, gas and cement (Chart 1(b)).



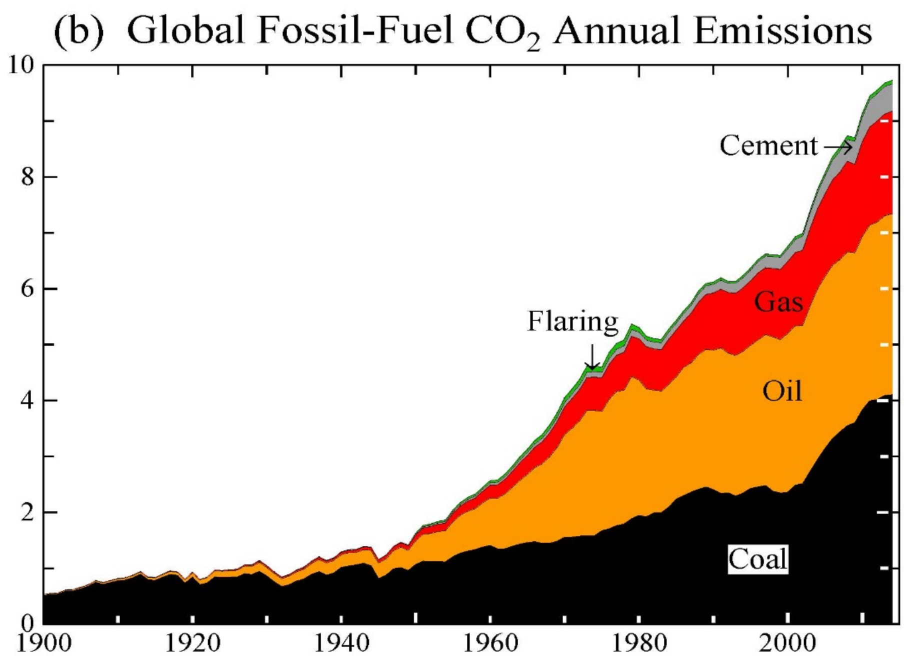


Chart 1: **CO_2 Annual Emissions From Fossil Fuel Use And Cement Manufacture**
Source: *Dangerous Climate Change* (**Exhibit 2** to this Declaration, at Fig. 1), updated through 2014 from http://www.columbia.edu/~mhs119/CO2Emissions/.

21. Our increased emissions are reflected, at least in part, in the rising concentration of atmospheric CO_2, as is illustrated in Chart 2[4] that is based on readings taken at the Mauna Loa, Hawaii, observatory. The CO_2, atmospheric level is now approximately 400 ppm, over 40 percent more than the preindustrial level.

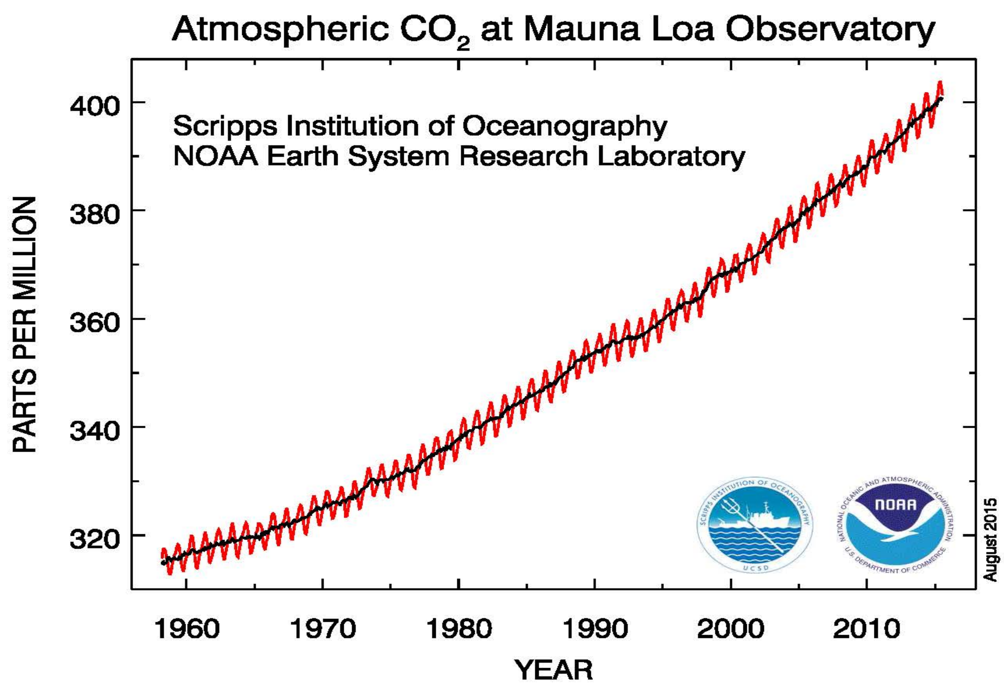


Chart 2: From Noaa's Earth System Research Laboratory
at http://www.esrl.noaa.gov/gmd/ccgg/trends/#mlo_full.

22. Moreover, the *increase* in the atmospheric CO_2 concentration is itself speeding up, as is illustrated in Chart 3.[5] The annual mean rate of CO_2 growth more than doubled from 0.85ppm in the 1960-70 period to 2.0ppm in 2000-2010.

4 *From* http://www.esrl.noaa.gov/gmd/ccgg/trends/#mlo_growth

5 *Id*.

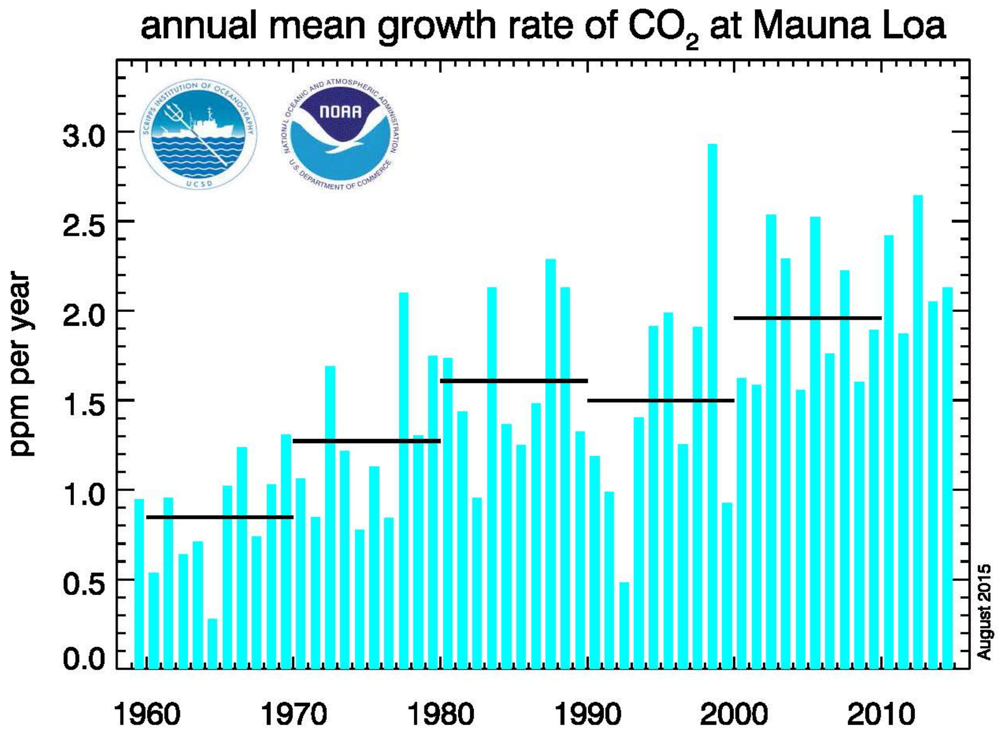


Chart 3: From Noaa's Earth System Research Laboratory
at http://www.esrl.noaa.gov/gmd/ccgg/trends/#mlo_growth.

23. This increased concentration of CO_2 and other GHGs in the atmosphere operates to reduce Earth's heat radiation to space, thus causing an energy imbalance – less energy going out than coming in. This imbalance causes Earth to heat-up until it again radiates as much energy to space as it absorbs from the sun.

24. In point of fact, warming of Earth caused by the increasingly thick CO_2 "blanket" persisted even during the recent five-year solar minimum from 2005-2010. Had changes in insolation been the dominant forcing, the planet would have had a negative energy balance in that period, when solar irradiance was at its lowest level in the period of accurate data, i.e., since the 1970s. Instead, even though much of the greenhouse gas forcing had been expended in causing observed 0.9°C global warming to date, the residual positive forcing from CO_2 emissions

overwhelmed the negative solar. This illustrates, unequivocally, that it is human activity, and not the sun, that is the dominant driver of recent climate change.

25. In terms of responsibility for our present predicament, I will note that it is true, as we can illustrate with the aid of Chart 4 (a) (left side), that in recent years, CO_2 emissions from China have exceeded those from the U.S.

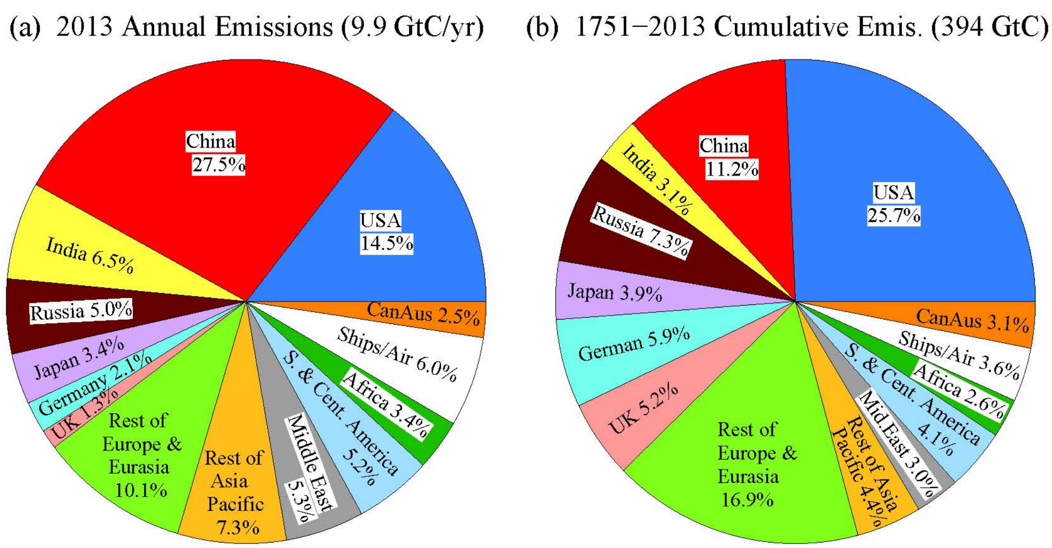


Chart 4: Fossil Fuel CO_2 Emissions
Source: *Dangerous Climate Change* (Exhibit 2 to this Declaration at Fig. 11)
updated through 2013 at http://www.columbia.edu/~mhs119/CO2Emissions/Emis_moreFigs/.

26. However, in light of the long residence time of CO_2 following its injection into the atmosphere, it is a nation's sum total of its emissions that is the more proper measure of its responsibility for already-realized and latent climate change. *See* Chart 4 (b) (right side). That chart illustrates that the United States is more responsible than any other for the present dangerously-highly atmospheric CO_2 concentration.

27. Here, I believe that a further word about the atmospheric residence time of CO_2 is in order, and we can do that with the aid of Chart 5 (left side).

Case 6:15-cv-01517-TC Document 7-1 Filed 09/10/15 Page 11 of 32

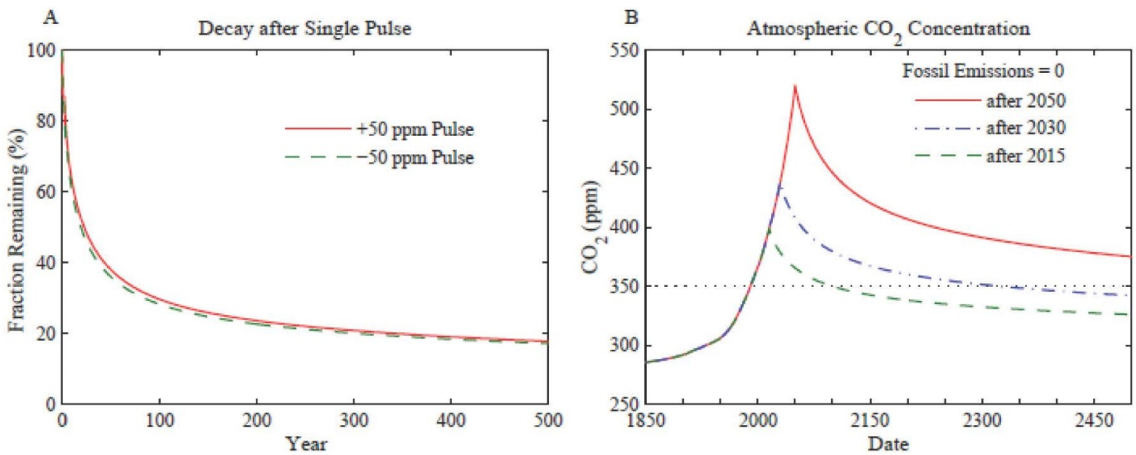


Chart 5: Decay Of Atmospheric CO_2 Perturbations
Source: *Dangerous Climate Change* (Exhibit 2 to this Declaration at Fig. 4). (A) Instantaneous injection or extraction of CO_2 with initial conditions at equilibrium. (B) Fossil fuel emissions terminate at the end of 2015, 2030, or 2050 and land use emissions terminate after 2015 in all three cases, i.e., thereafter there is no net deforestation.

28. A pulse of CO_2 injected into the air decays by half in about 25 years, as CO_2 is taken up by the ocean, biosphere and soil, but nearly one-fifth remains in the atmosphere after 500 years. Indeed, that estimate is likely optimistic, in light of the well-known nonlinearity in ocean chemistry and saturation of carbon sinks, implying that the airborne fraction probably will remain larger for a century and more. It requires hundreds of millennia for the chemical weathering of rocks to eventually deposit all of this initial CO_2 pulse on the ocean floor as carbonate sediments.

29. The critical point here is that carbon from fossil fuel burning remains in the climate system, with much of it in the atmosphere, and thus continues to affect the climate system for many millennia.

30. It is in part for this reason – the atmospheric persistence of CO_2 – that our national contribution to the problem is so large. Moreover, we can observe that, as compared with that of other major CO_2-emitting nations, our national contribution to the global climate crisis is not only

largest in absolute amount (Chart 4b), it dwarfs the contributions of the most populous nations on a per capita basis. Chart 6.

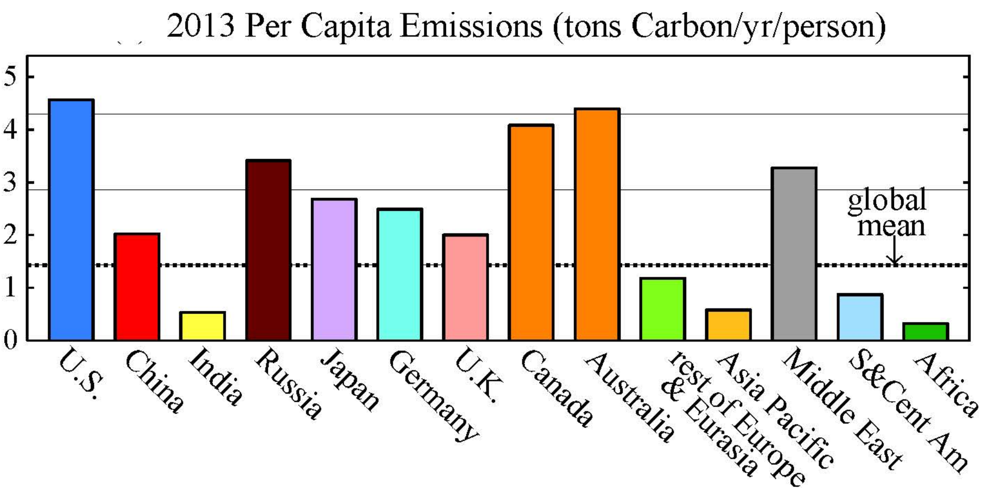


Chart 6: **Cumulative Per Capita Carbon Dioxide Emissions**
Source: www.columbia.edu/~mhs119/YoungPeople/.

31. Turning, now to Chart 7, we see the upward march of recent average global surface temperature.

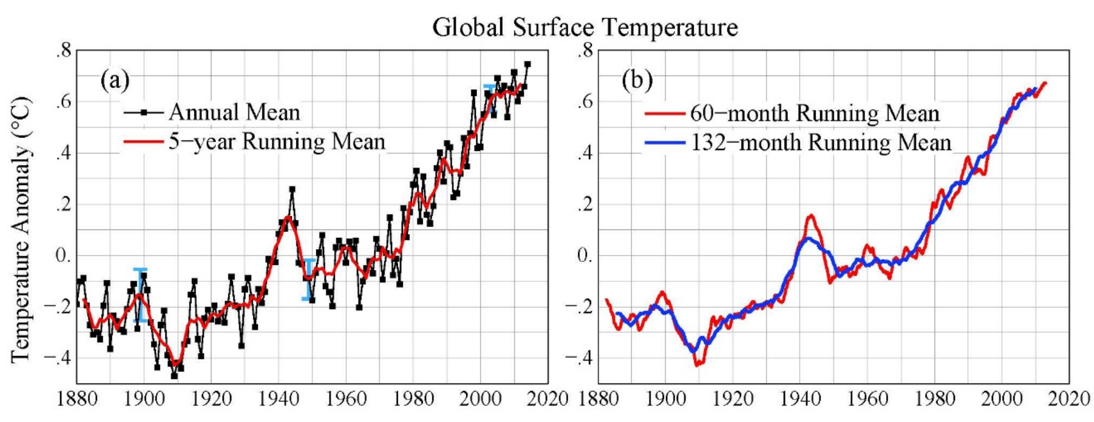


Chart 7: **Global Surface Temperature Anomaly (60-Month And 132-Month Running Means) With A Base Period Of 1951-1980**
Source: *Dangerous Climate Change* (Exhibit 2 to this Declaration at Fig. 3), updated at [http://www.columbia.edu/~mhs119/Temperature/.](http://www.columbia.edu/~mhs119/Temperature/)

32. Earth has now warmed about 0.9°C above the pre-industrial level. That is now close to, and probably slightly above, the prior maximum of the Holocene era – the period of relatively stable climate over the last 10,000 years that has enabled human civilization to develop.

33. The warming increases Earth's radiation to space, thus reducing Earth's energy imbalance. However, because of the ocean's great thermal inertia, it requires centuries for the climate system to reach a new equilibrium consistent with a changed atmospheric composition. The planet's energy imbalance confirms that substantial additional warming is "in the pipeline". That energy imbalance is now measured by an international fleet of more than 3000 submersible floats that plumb the depths of the world's ocean measuring the increasing heat content.

34. Earth's energy imbalance now averages about 0.6 Watts/m^2 averaged over the entire planet, but I am uncertain whether this conveys to the Court the scale of what is going on. I can note that the total energy surplus is 300 trillion joules per second, but that large number may still be insufficiently evocative. Accordingly, it may be more useful to observe, and with equal validity, that Earth's energy imbalance is equivalent to exploding more than 400,000 Hiroshima atomic bombs per day, 365 days per year. That is how much extra energy Earth is now gaining each day because of our use of the atmosphere as a waste dump for our carbon pollution.

35. We can turn now to Chart 8.

/ / /

/ / /

/ / /

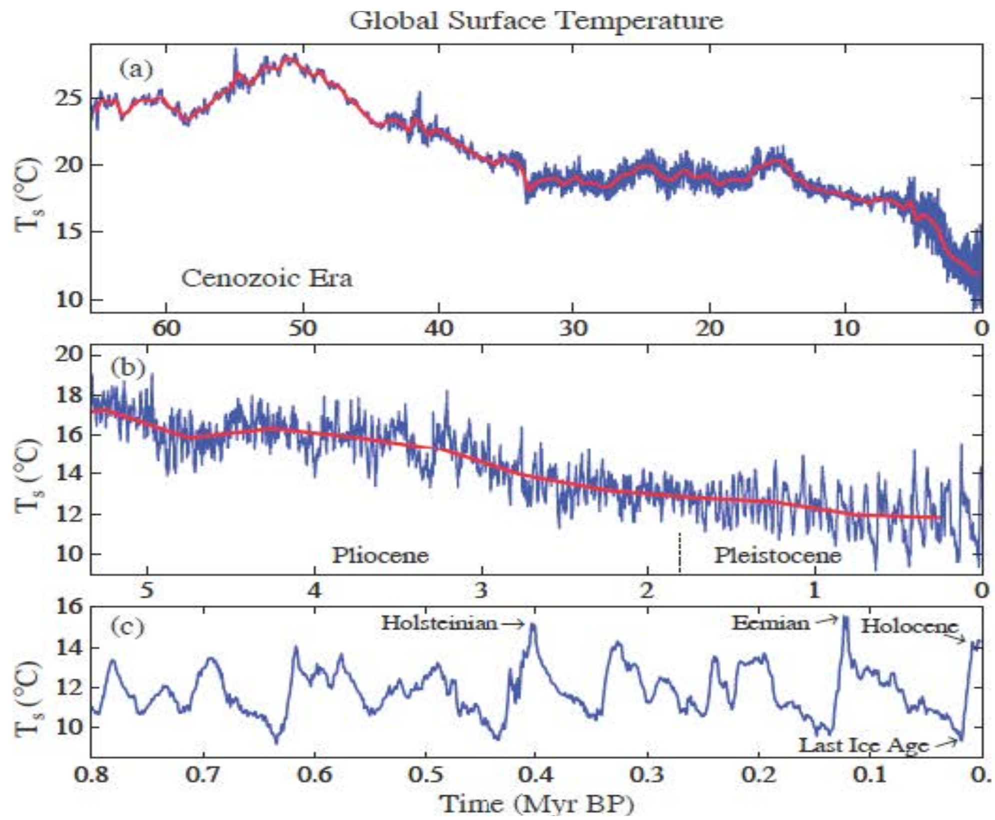


Chart 8: **Surface Temperature Estimate for the Past 65.5 Myr, Including An Expanded Time Scale for (B) The Pliocene and Pleistocene and (C) The Past 800 000 Years**
Source: J. Hansen, et al, *Climate Sensitivity, Sea level and Atmospheric Carbon Dioxide*, Phil Trans R Soc A (2013), Fig. 4.

36. Here, we summarize the average global surface temperature record of the last 65 million years. This record is based on high-resolution ice core data covering the most recent several hundred thousand years, and ocean cores on time scales of millions of years. It provides us with insight as to global temperature sensitivity to external forcings such as added CO_2, and sea level sensitivity to global temperature. It also provides quantitative information about so-called "slow" feedback processes – such as melting ice sheets and lessened surface reflectivity attributable to darker surfaces resulting from melting ice sheets and reduced area of ice.

37. Several relevant conclusions can be drawn. First, the mechanisms that account for the relatively rapid oscillations between cold and warm climates were the same as those operating today. Those past climate oscillations were initiated not by fossil fuel burning, but by slow insolation changes attributable to perturbations of Earth's orbit and spin axis tilt. However, the mechanisms that caused these historical climate changes to be so large were two powerful amplifying feedbacks: the planet's surface albedo (its reflectivity, literally its whiteness) and atmospheric CO_2.

38. Second, the longer paleoclimate record shows that warming coincident with atmospheric CO_2 concentrations as low as 450 ppm may have been enough to melt most of Antarctica. Global fossil fuel emissions – towards which, as I noted above, our nation has contributed more than any other – have already driven up the atmospheric CO_2 concentration to approximately 400 ppm – up from 280 ppm of the preindustrial era.

39. I conclude that the present level of CO_2 and its warming, both realized and latent, is already in the dangerous zone. Indeed, we are now in a period of overshoot, with early consequences that are already highly threatening and that will rise to unbearable unless action is taken without delay to restore energy balance at a lower atmospheric CO_2 amount. We can turn now to a brief review of the increasingly unacceptable, but still avoidable, consequences.

III. UNABATED EMISSIONS MAY DEVASTATE OUR COASTS, CIVILIZATION AND NATURE AS WE KNOW IT

40. I will start with the ocean, in light of our most recent research.

41. While I have postulated previously that major ice sheet disintegration and resulting sea level rise is likely to be nonlinear in the event of continued high fossil fuel impacts, my concern had been based largely on heuristic grounds. Now, utilizing multiple lines of evidence – including satellite gravity measurement, surface mass balances, and satellite radar altimetry – it

has become clear, regrettably, that ice mass losses from Greenland, West Antarctica and parts of East Antarctica are growing nonlinearly, with doubling times so far this century of approximately 10 years.

42. My colleagues and I expect the growth rate for ice mass loss in Greenland to slow, based on the most recent few years of data, but because of amplifying feedbacks described in our paper we also think it likely that Antarctic ice mass loss will continue to climb exponentially – again, if fossil fuel emissions are not rapidly abated. This prospect alone cries out for urgent national and international action to constrain carbon pollution, considering that complete disintegration of the Totten glacier in East Antarctica could raise sea levels by approximately 6-7m; that ice fronted by the Cook glacier in East Antarctica could add 3-4m of sea rise; and that West Antarctic ice fronted by Amundsen Sea glaciers have the potential to raise sea level an additional *3-4m*. *See* **Exhibit 3** at 41.

43. In the light of this and related information, we have concluded that humanity faces "nearly certainty of eventual sea level rise of at least . . . 5-9m if fossil fuel emissions continue on a business-as-usual course." *See* **Exhibit 3** at PDF page 31. Much of the U.S. eastern seaboard,[6] as well as low-lying areas of Europe, the Indian sub-continent, and the Far East, would then be submerged. *See* Chart 9.

[6] Western U.S. cities too are vulnerable, to the degree that parts of them are relatively low-lying. It is estimated, for example, that sea level rise of "only" 10 feet (approximately 3 meters) will inundate over 4,000 acres (and over 3,000 homes) in Seattle, nearly 3,000 acres (and over 13,000 homes) in San Francisco, and over 4,000 acres (and nearly 10,000 homes) in San Diego. *See* Climate Central's "Surging Seas" project at http://sealevel.climatecentral.org/ .

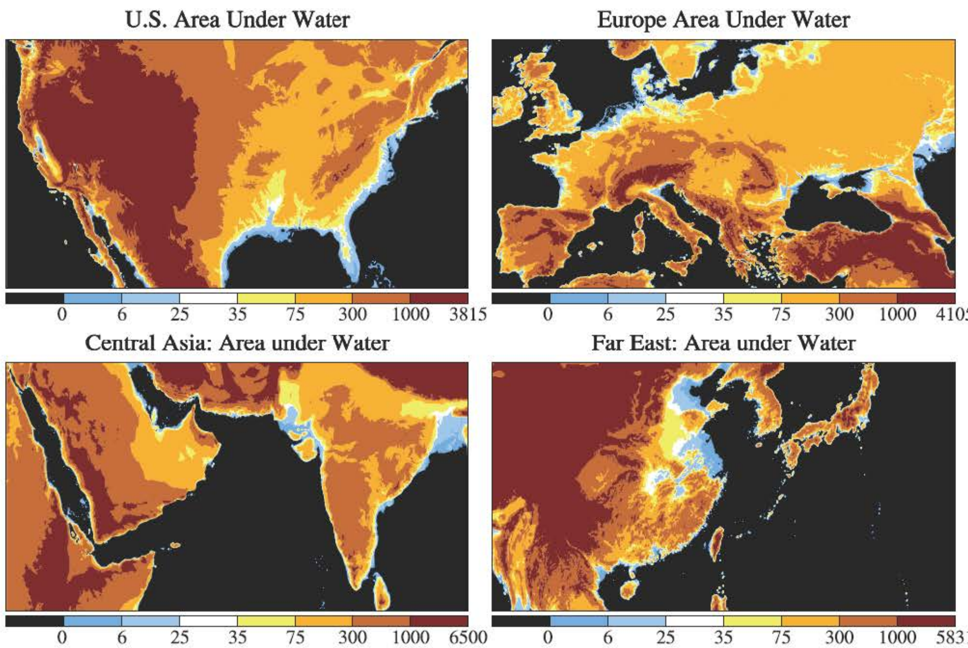


Chart 9: **Areas (Light And Dark Blue) That Nominally Would Be Under Water For 6 And 25 M Sea Level Rise**
Source: Climate Science, Awareness, and Solutions, Earth Institute, Columbia University (2015).

44. That order of sea level rise would result in the loss of hundreds of historical coastal cities worldwide, with incalculable economic consequences. It would also create hundreds of millions of global warming refugees from highly populated low-lying areas, and thus likely cause or exacerbate major international conflicts.[7]

45. To avoid such a calamity, sea level rise must be recognized as a key limit on any conceivably allowable human-made climate forcing and atmospheric CO_2 concentration, with

[7] In addition, strong temperature gradients caused by ice melt freshening is likely to increase baroclinicity and provide energy for more severe weather events, including in the North Atlantic. This set of circumstances will drive the powerful superstorms of our future. Some of these impacts are beginning to occur sooner in the real world than in our climate model. *See* **Exhibit 3** at pdf 31.

fossil fuel emissions and land use changes constrained accordingly.[8] As discussed, ice sheet melting has now commenced even though global warming to date measures "only" 0.9°C above the pre-industrial period. This is consistent with the relevant paleoclimate evidence showing a multi-meter rise in sea level in the late Eemian period, approximately 125K years ago, when temperature was at most ~2°C warmer than pre-industrial climate (at most ~1°C warmer than today). This, in itself, and quite apart from the additional harm to terrestrial systems that must also be considered, implies that national and international goals and targets that aim to limit global warming to no more than 2°C run an unacceptably high risk of global catastrophe.

46. An important effect for the coming period of large scale ice sheet melting, in our view, is that the discharge of ice and cold fresh water will expand sea ice cover and result in ocean surface, regional and global cooling effects. *See* **Exhibit 3** at pdf 3-11. For varying periods, these effects would mask some of the global warming that would otherwise result from projected high CO_2 levels. The temporary surface cooling, however, would be coincident with a further increase in the planet's energy imbalance, with added energy pumped into the ocean, and there be available, at Antarctica and Greenland, to further melt the subsurface shelves that, at present, restrain several of the planet's major ice sheets at their grounding lines. *See* **Exhibit 3** at pdf 18.

47. Upon cessation of ice sheet disintegration and freshwater discharge, global temperature will recover – with the time period for such recovery depending on the amount of ice melt (and sea level rise), and with geographical, geophysical and oceanic circulation factors detailed in our recent study. *See* **Exhibit 3** at pdf 11.

---

[8] This is so, as we wrote in "Ice Melt, Sea Level Rise and Superstorms," **Exhibit 3** at pdf 32, in light of the "extreme sensitivity of sea level to ocean warming and the devastating economic and humanitarian impacts of a multi-meter sea level rise."

48. With respect to other important natural and human systems, to which I will now turn, the impacts of global warming – including the renewed warming – will depend in part on the magnitude of Earth's energy imbalance, and that, in turn, will be controlled by the level of excess atmospheric CO_2. As I have noted already, global warming to date measures "only" 0.9°C above the pre-industrial period, and yet, that level of warming has already begun to have a widespread effect on natural and human systems.

49. For example, mountain glaciers, the source of fresh water to major world rivers during dry seasons, are receding rapidly all around the world. To cite a close-to-home example, glaciers in iconic Glacier National Park appear to be in full retreat: In 1850, according to the Park Service, Glacier had 150 glaciers measuring larger than twenty-five acres. Today, it has just twenty-five.

50. As well, tropospheric water vapor and heavy precipitation events have increased, as we would expect. A warmer atmosphere holds more moisture, thus enabling precipitation to be heavier and cause more extreme flooding. Higher temperatures, on the other hand, increase evaporation and can intensify droughts when they occur, as can the expansion of the subtropics that occurs as a consequence of global warming.

51. Coral reef ecosystems, harboring more than 1,000,000 species as the "rainforests" of the ocean, are impacted by a combination of ocean warming, acidification from rising atmospheric CO_2, and other human-caused stresses, resulting in a 0.5-2% per year decline in geographic extent.

52. World health experts have concluded with "very high confidence" that climate change already contributes to the global burden of disease and premature death with expansion of

infectious disease vectors. Increasing climate variability is being examined as a possible contributor to the expansion of Ebola.

53. Subtropical climate belts have expanded, contributing to more intense droughts, summer heat waves, and devastating wildfires. Further, summer mega-heat-waves, such as those in Europe in 2003, the Moscow area in 2010, Texas and Oklahoma in 2011, Greenland in 2012, Australia in 2013, *Australia and California in 2014, and India, France and Spain this year (2015),* have become more widespread.[9] The probability of such extreme heat events has increased by several times because of global warming, and the probability will increase even further if fossil fuel emissions continue to be permitted, so that global warming becomes locked in or rendered increasingly severe.

54. I have already mentioned the unparalleled calamity that the loss of scores of coastal cities to rapid sea level rise presents to human civilization. But I should mention that many other impacts also will abound.

55. For example, acidification stemming from ocean uptake of a portion of increased atmospheric CO_2 will increasingly disrupt coral reef ecosystem health, with potentially devastating impacts to certain nations and communities. Inland, fresh water security will be compromised, due to the effects of receding mountain glaciers and snowpack on seasonal freshwater availability of major rivers.

56. As to human health: increasing concentrations of CO_2 and associated increased global temperatures will deepen impacts, with children being especially vulnerable. Climate

[9] Climate researchers in Oregon consider that state's recent heat and dry spell to be consistent with these trends, with the month of June, 2015 being said to be the warmest on record in much of the state. *See* Oregon Climate Service at http://ocs.oregonstate.edu/ . In general, however, local observations of climate (heat) extremes are illustrative of what will occur with the increasing atmospheric CO_2 concentration, but I will caution that other, more stochastic, variables usually will be in play as well.

threats to health move through various pathways, including by placing additional stress on the availability of food, clean air, and clean water. Accordingly, unabated climate change will increase malnutrition and consequent disorders, including those related to child growth and development. It will increase death and illness associated with COPD, asthma, and other respiratory distress triggered by worsened allergies. Unabated emissions will also produce other injuries from heat waves; floods, storms, fires and droughts, and it will increase cardio-respiratory morbidity and mortality associated with increased ground-level ozone.

57. With regard to other species, we see that climate zones are already shifting at rates that exceed natural rates of change; this trend will continue as long as the planet is out of energy balance. As the shift of climate zones becomes comparable to the range of some species, the less mobile species will be driven to extinction. According to the UN Panel on Climate Change, with global warming of 1.6°C or more relative to pre-industrial levels, 9-31 percent of species are anticipated to be driven to extinction, while with global warming of 2.9°C, an estimated 21-52 percent of species will be driven to extinction. These temperature/extinction thresholds will not be avoided absent concerted, rational action on carbon emissions.

58. At present, we remain on track to burn a significant fraction of readily available fossil fuels, including coal, oil, natural gas, and tar sands, and so to raise average surface temperature, over time, to far above pre-industrial levels.

59. High global surface temperatures have been recorded previously, in the age of mammals, with some successful adaptation through evolution of higher surface-area-to-mass ratio body types – for example transient dwarfing of mammals and even soil fauna. However, human-made warming is occurring rapidly and will be fully realized in only centuries, as opposed to millennia, thus providing little opportunity for evolutionary dwarfism to alleviate impacts of

global warming. Along with several colleagues, I have been forced to conclude that the large climate change that would result from burning all or most fossil fuels threatens the survival of humanity.

60. All of which brings me to my third point.

IV. RESTORATION OF OUR CLIMATE SYSTEM, AND SO PROTECTION OF OUR FUTURE, IS STILL POSSIBLE, BUT WE MUST ACT WITH REASON, COURAGE, AND NO FURTHER DELAY

61. As I indicated above, the energy imbalance of Earth is about 0.6 W/m2. In the light of that imbalance, colleagues and I have calculated the level to which atmospheric CO_2 must be drawn down in order to increase Earth's heat radiation to space by the same amount and thus restore energy balance – the fundamental requirement to stabilize climate and avoid further dangerous warming.

62. The measured energy imbalance indicates that CO_2 must be reduced to a level below 350 ppm, assuming that the net of other human-made climate forcings remains at today's level. Specification now of a CO_2 target more precise than <350 ppm is difficult due to uncertain future changes of radiative forcing from other gases, aerosols and surface albedo, but greater precision should be feasible during the time that it takes to turn around CO_2 growth and approach the initial 350 ppm target.

63. Let us return, for a moment, to Chart 5, so as to consider again the question of delay. On the left side of the chart, the long-residence time for atmospheric CO_2 is illustrated. It is reflected in the length of time it would take to return CO_2 to lower concentrations even if, as indicated on the right side of the chart, fossil fuel emissions were to cease entirely.

64. Of course, an abrupt cessation of all CO_2 emissions, whether this year or in 2030, is unrealistic. Industry, other business, and consumers all need time to retool and reinvest in emission-free options to fossil fuels.

65. Accordingly, we have evaluated emissions reduction scenarios to devise the path that is both technically and economically feasible, while being sufficiently rigorous to constrain the period of "carbon overshoot" and avoid calamitous consequences (greatly accelerated warming, ecosystem collapse, and widespread species extermination). *See* Chart 10.

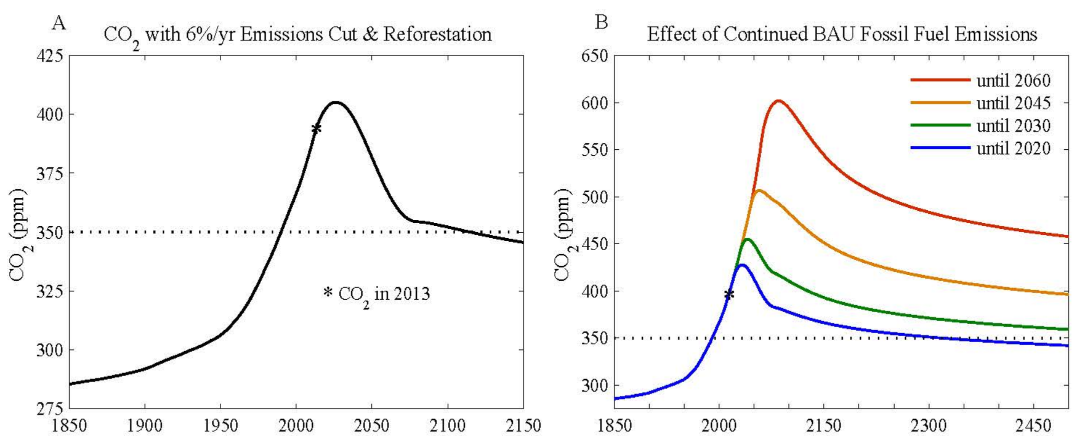


Chart 10: **Atmospheric CO_2 If Fossil Fuel Emissions Are Reduced.**
(A) 6% Or 2% Annual Cut Begins In 2013 And 100 GRC Reforestation Drawdown Occurs In 2031-2080, (B) Effect Of Delaying Onset Of Emission Reductions.
Source: *Dangerous Climate Change* (Exhibit 2 to this Declaration at Fig. 5).

66. Our analysis prescribes a glide path towards achieving energy balance by the end of the century. It is characterized by large, long-term global emissions reductions (of approximately 6 percent annually, if commenced this year), coupled with programs to limit and reverse land use emissions via reforestation and improved agricultural and forestry practices (drawing down approximately 100 GtC by the year 2100).

67. These actions could achieve the goal of restoring the atmosphere to approximately 350 ppm within this century if the plan were commenced without delay, and then adhered to. As I have indicated, such action is minimally needed to restore earth's energy balance, preserve the planet's climate system, and avert irretrievable damage to human and natural systems – including agriculture, ocean fisheries, and fresh water supply – on which civilization depends. However, consistent with the abrupt phase out scenarios discussed in the prior paragraph, if rapid annual emissions reductions are delayed until 2030, then the global temperature will remain more than 1°C higher than preindustrial levels for about 400 years. Were the emissions cessation only to commence after 40 years, then the atmosphere would not return to 350 ppm CO_2 for nearly 1000 years. Overshooting the safe level of atmospheric CO_2 and the safe range of global ambient temperature for anything approaching these periods will consign succeeding generations to a vastly different, less hospitable planet.

68. Considered another way, the required rate of emissions reduction would have been about 3.5% per year if reductions had started in 2005 and continued annually thereafter, while the required rate of reduction, if commenced in 2020, will be approximately 15% per year. Accordingly, the dominant factor is the date at which fossil fuel emission phase out begins, again presuming the rate of annual emissions reductions thereafter are sustained.

V. THE FUNDAMENTAL RIGHTS OF MY GRANDDAUGHTER SOPHIE, OTHER CHILDREN, AND FUTURE GENERATIONS TO A HABITABLE PLANET

69. With all of the above having now been said, and serving as background, I can return, finally, and briefly, to consider the nature of the violations of the rights of my granddaughter and future generations that are properly attributable our government's continued permitting, leasing, and other support for fossil fuel exploitation and expansion projects--

particularly in the absence of any countervailing, coherent, effective government program to rapidly reduce atmospheric CO_2 to a safe level.

70. In this, I include our government's approval of the Jordan Cove project at Coos Bay, Oregon. To be specific, in the context of US emissions to date and the present global climate crisis those emissions have done much to engender, the additional emissions stemming from Jordan Cove will work only to further increase the atmospheric concentrations of CO_2, and thus to further increase Earth's energy imbalance – *thereby driving our planet towards and potentially beyond irretrievable climate system tipping points*.

71. This is so because, by exacerbating or locking-in Earth's energy imbalance, such government action jeopardizes the signal features of the relatively benign and favorable climate system that, over the last 10,000 years, enabled civilization to develop and nature to thrive, as I have discussed. These features included relatively stable coastlines, moderate weather, fertile soils, and dependable hydrological systems – the natural capital on which the lives of Plaintiffs depend no less than did the lives of their parents and *their* forebears.

72. As well, present and future government action that exacerbates or locks-in Earth's energy imbalance risk economic collapse, social disintegration, and the loss of essential natural and human services, as I have discussed. The resulting diminution of Plaintiffs' life prospects – their compromised ability to earn a living, to meet their basic human needs, to safely raise families, to practice their religious and spiritual beliefs, and otherwise to lead dignified lives – is a predictable if not intended result of the government action.

73. In addition, where such government action exacerbates or locks-in Earth's energy imbalance that, in turn, predictably will lead to the climate change-driven inundation, burning, or other destruction of the value of property in which Plaintiffs hold interests. These will include the

homes, farms and other valuable property that their parents or grandparents own and that Plaintiffs will inherit.

74. Further, these government actions, in consequence of their long-term impacts on Earth's climate system and the thermal inertia of the ocean, will disproportionately impose harsh burdens on Plaintiffs. If fossil fuel emissions are not systematically and rapidly abated, as I have discussed above – including in the materials that I have incorporated by reference – then Youth and Future Generations Plaintiffs will confront what reasonably only can be described as, at best, an inhospitable future. That future may be marked by rising seas, coastal city functionality loss, mass migrations, resource wars, food shortages, heat waves, mega-storms, soil depletion and desiccation, freshwater shortage, public health system collapse, and the extinction of increasing numbers of species. That is to mention only the start of it. At this late stage it is important not to sugarcoat the fundamental assault on their right to equal protection of the law: While prior generations and, to a certain extent, some in our present generation have benefitted and, even, been enriched by the exploitation of fossil fuels, our children and their progeny will not similarly benefit. Indeed, the impact on Plaintiffs' will be nearly completely to the contrary, as I have discussed.

75. Closely-related to the above, our government's continued permitting and promotion of the fossil fuel enterprise now impairs and increasingly will compromise the fundamental natural resources on which Plaintiffs will depend. Again, these are the fundamental resources on which the prior and present generations have relied, and on which Plaintiffs now and in the future must rely. They include the air, freshwater, the oceans and stable shores, the soil and its agronomic capacity, the forests and its wildlife, biodiversity on earth, and the planet's climate system in a form conducive to civilization, humanity and nature as we know it.

76. Furthermore, it is clear to me that Plaintiffs' right to a government that retains any significant capacity to address the climate crisis adequately is violated by prior and present government actions that exacerbate or lock-in our planet's energy imbalance. In time and, as I have argued, likely within the century, such action will irretrievably damage our planet's favorable climate system. Once begun, for example, collapsing and disintegrating ice sheets will not readily be reformulated – certainly not within a timeframe relevant to present and foreseeable generations. The loss of species too is irretrievable. Many are adapted to specific climate zones, so those species adapted to polar and alpine regions will have no place to run. Present and pending actions by our government now must be viewed in the context of a climate crisis that our government to date has done so much to bring about. Action is required to preserve and restore the climate system such as we have known it in order for the planet as we have known it to be able to continue adequately to support the lives and prospects of young people and future generations. But that cannot be done effectively by future governments if ours continues to exacerbate the planet's energy imbalance and press our planet towards irretrievable tipping points from which there can be no practical opportunity to return.

77. To further explain this last point, I will note that earlier in this declaration I discussed our nation's outsized role in creating, through its CO_2 emissions, our present emergency with respect to the planet's climate system. *See supra*, text surrounding Chart 4 and Chart 6. Other nations are keenly aware of this basic fact including, most importantly, China. It is, accordingly, worthwhile here – in the context of considering responsibility to resolve the present crisis and preserve a habitable climate system – to consider further these top two emitters' role.

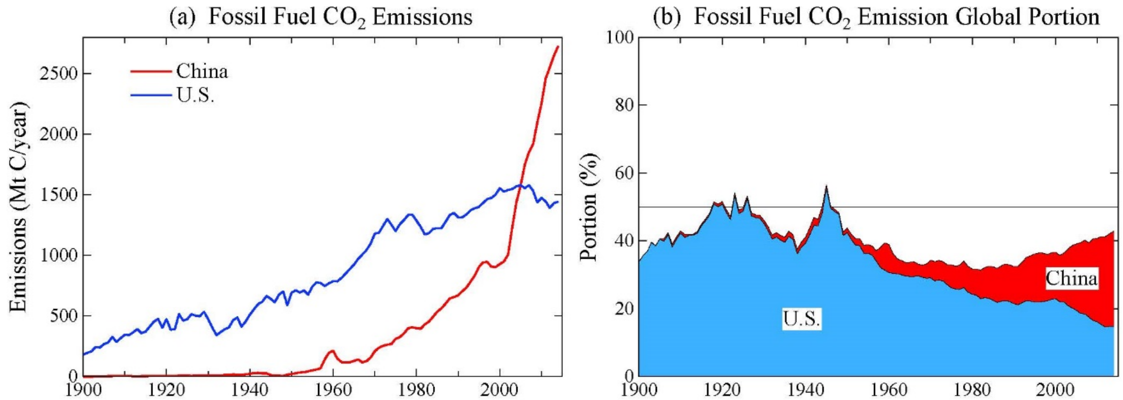


Chart 11: **Top Two Annual Emitters And Their Cumulative Emissions**
(a) Fossil fuel CO_2 Emissions, 1990 Through 2014, (B) Cumulative Shares: U.S. And China
Source: Climate Science, Awareness and Solutions, based on data from ORNL through 2011, updated with BP data through 2014.

78. China's annual CO_2 emissions caught those of the United States in 2005 and then rapidly surpassed U.S. emissions. *See* Chart 11 (a) (left side). However, any nation's contribution to climate change is proportional to its cumulative emissions over time.[10] China's responsibility for global climate change remains a fraction of that of the U.S., despite China's much larger population. *See* Chart 11 (b) (right side). Specifically, China's share of global fossil fuel CO_2 emissions through 2014 is 11.6 percent while the United States share is 25.5 percent.

79. Accordingly, in the light of our preponderant role, the United States has special responsibility for helping to solve the global emissions problem. The remaining carbon "budget" – the amount of emissions that can be tolerated while still allowing the possibility of stabilizing climate – is very small. As we have noted, climate stability requires that global emissions decline by at least 6% per year. In effect, the United States burned not only its fair share of the total (cumulative) carbon budget, it also burned much of China and India's fair shares.

[10] Hansen, J., *et al.*, Dangerous human-made interference with climate: A GISS modelE study. *Atmos. Chem. Phys.*, **7**, 2287-2312, doi:10.5194/acp-7-2287-2007.

80. It is instructive to examine the emissions of China and India, which are shown in Chart 12. China is the #1 global emitter of CO_2 and India is #3, with the United States being #2. Together the three nations emit about half of global emissions, i.e., the same as the other 190 nations of the world combined. Two conclusions leap out from Chart 12. First, emissions in those nations are accelerating rapidly. Second, most of their emissions are from coal burning. (Note that the scale of the vertical axis is different for China and India. India is in an earlier stage of economic development and its emissions are as yet much smaller than China's.)

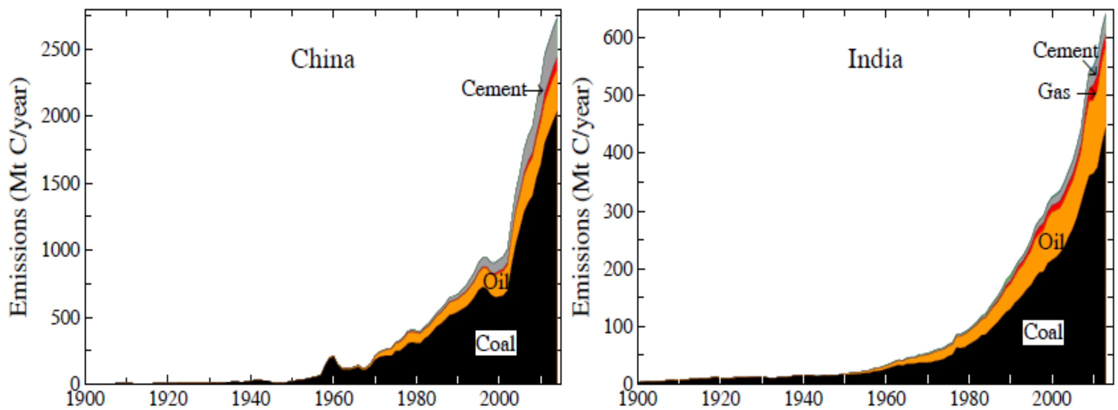


Chart 12: CO_2 Emissions From China (Left Side) And India (Right Side)
Graphic from Climate Science, Awareness and Solutions, utilizing data from the Carbon Dioxide Information Analysis Center and the BP Statistical Review of World Energy (2014).

81. The rapid growth of coal emissions is both a threat to global climate and a source of hope. If coal can be replaced with carbon-free energy, a huge reduction of global emissions becomes possible. In view of the responsibility of the United States for the excess CO_2 in the air today, as well as the fact that U.S. citizens will suffer the consequences of global emissions, it is incumbent upon the U.S. to vigorously assist China with the technology required to replace coal burning. Yet the U.S. government, and its chief executive, the President have not undertaken such actions, leaving today's young people and future generations extremely vulnerable. Indeed,

U.S. actions to date have been mostly rhetorical.[11] Instead, our government including, especially, the U.S. President, should marshal every available tool, talent, and resource to address and resolve the present crisis with honesty and without further delay.

82. Young people have multiple rights that are guaranteed by our Constitution, including equal protection of the law, equal rights to enjoy life, liberty, property, and the pursuit of happiness – rights that should not be denied without due process. It is the duty of all branches of government to protect those rights. Specifically, it is a duty of the chief executive, the President, to lead and propose and pursue policies that achieve the required ends, as opposed to ineffectual actions that are demonstrably far short of what is needed.

83. The essential step, in my view and that of other experts, including economists,[12] is an accord establishing a growing price on CO_2 emissions, which would lead over time to their phase-out. Agreement upon such a domestic fee by major emitters, most notably the United States and China, with a border duty on products from nations that do not have an equivalent domestic carbon fee, would be expected to lead to widespread global movement toward carbon-free energies.

[11] EPA's much-vaunted "Clean Power Plan," for example, actually allows U.S. coal-fired power plants to continue to operate for decades, and that Agency itself anticipates that, under the rule, power plant emission reductions will proceed at a slower pace than occurred in the ten-year period *prior* to the rule's enactment.

[12] These include three co-authors of our 2013 PLOS One study. *See* **Exhibit 2**. The government also has understood the central importance of a rising carbon price, and for at least 25 years. *See*, e.g., Congressional Office of Technology Assessment, *Changing by Degrees: Steps To Reduce Greenhouse Gases* (1991) at 15 ("a particularly effective way of targeting the heaviest economic sanctions against the worst emitters of CO_2."). As colleagues and I noted in 2013, **Exhibit 2** at 19, "[a] rising carbon fee is the *sine qua non* for fossil fuel phase out."

84. I could go on, but will not so as to show mercy on the Court. Accordingly, I end here with a summary statement, in the light of the foregoing material that I have outlined and referenced, and with the offer to further explain my views and reasoning at the Court's request.

85. Simply put: Our government's persistent permitting and underwriting of fossil fuel projects serves now to further disrupt the favorable climate system that to date enabled human civilization to develop. In order to preserve a viable climate system, our use of fossil fuels must be phased out as rapidly as is feasible. Only government can ensure this will be done. Instead, our government seeks approval for permitting of fossil fuel projects that would slam shut the narrowing window of opportunity to stabilize climate and ensure a hospitable climate and planet for young people and future generations. These projects only allow our government to shirk its duty. Our government's permitting of additional, new, or renewed fossil fuel projects is entirely antithetical to its fundamental responsibility to our children and their posterity. Their fundamental rights now hang in the balance.

I am prepared, as necessary, to further explain or elaborate on any of the points I have made in this declaration, as warranted, for the Court.

I, James E. Hansen, declare under penalty of perjury under the laws of the United States of America that the foregoing constitutes my true and correct written testimony in the matter *Xiuhtezcatl Tonatiuh M. et al. v. the United States of America et al.*, No. __, United States District Court, District of Oregon.

I declare under penalty of perjury under the laws of the State of Oregon that the foregoing is true and correct.

Executed this 11th day of August, 2015 in New York City, New York.

James E Hansen

DR. JAMES E. HANSEN

James E. Hansen

Columbia University Earth Institute, Climate Science, Awareness and Solutions
Interchurch Building, 475 Riverside Drive, Room 239T, New York, NY 10115 jimehansen@gmail.com

1-paragraph bio/introduction:
Dr. James Hansen, formerly Director of the NASA Goddard Institute for Space Studies, is an Adjunct Professor at Columbia University's Earth Institute, where he directs a program in Climate Science, Awareness and Solutions. Dr. Hansen is best known for his testimony on climate change in the 1980s that helped raise awareness of global warming. He is a member of the U.S. National Academy of Sciences and has received numerous awards including the Sophie and Blue Planet Prizes. Dr. Hansen is recognized for speaking truth to power and for outlining actions needed to protect the future of young people and all species on the planet.

1-long-paragraph bio:
Dr. James Hansen, formerly Director of the NASA Goddard Institute for Space Studies, is an Adjunct Professor at Columbia University's Earth Institute, where he directs a program in Climate Science, Awareness and Solutions. He was trained in physics and astronomy in the space science program of Dr. James Van Allen at the University of Iowa. His early research on the clouds of Venus helped identify their composition as sulfuric acid. Since the late 1970s, he has focused his research on Earth's climate, especially human-made climate change. Dr. Hansen is best known for his testimony on climate change to congressional committees in the 1980s that helped raise broad awareness of the global warming issue. He was elected to the National Academy of Sciences in 1995 and was designated by Time Magazine in 2006 as one of the 100 most influential people on Earth. He has received numerous awards including the Carl-Gustaf Rossby and Roger Revelle Research Medals, the Sophie Prize and the Blue Planet Prize. Dr. Hansen is recognized for speaking truth to power, for identifying ineffectual policies as greenwash, and for outlining actions that the public must take to protect the future of young people and other life on our planet.

3-paragraph bio:
Dr. James Hansen, formerly Director of the NASA Goddard Institute for Space Studies, is an Adjunct Professor at Columbia University's Earth Institute, where he directs a program in Climate Science, Awareness and Solutions. He was trained in physics and astronomy in the space science program of Dr. James Van Allen at the University of Iowa, receiving a bachelor's degree with highest distinction in physics and mathematics, master's degree in astronomy, and Ph. D. in physics in 1967. Dr. Hansen was a visiting student, at the Institute of Astrophysics, University of Kyoto and Dept. of Astronomy, Tokyo University, Japan from 1965-1966. He received his Ph.D. in physics from the University of Iowa in 1967. Except for 1969, when he was an NSF post-doctoral scientist at Leiden Observatory under Prof. H.C. van de Hulst, he has spent his post-doctoral career at NASA GISS.

In his early research Dr. Hansen used telescopic observations of Venus to extract detailed information on the physical properties of the cloud and haze particles that veil Venus. Since the mid-1970s, Dr. Hansen has focused on studies and computer simulations of the Earth's climate, for the purpose of understanding the human impact on global climate. He is best known for his testimony on climate change to Congress in the 1980s that helped raise broad awareness of the global warming issue. In recent years Dr. Hansen has drawn attention to the danger of passing climate tipping points, producing irreversible climate impacts that would yield a different planet from the one on which civilization developed. Dr. Hansen disputes the contention, of fossil fuel interests and governments that support them, that it is an almost god-given fact that all fossil fuels must be burned with their combustion products discharged into the atmosphere. Instead Dr. Hansen has outlined steps that are needed to stabilize climate, with a cleaner atmosphere and ocean, and he emphasizes the need for the public to influence government and industry policies.

Dr. Hansen was elected to the National Academy of Sciences in 1995 and, in 2001, received the Heinz Award for environment and the American Geophysical Union's Roger Revelle Medal. Dr. Hansen received the World Wildlife Federation's Conservation Medal from the Duke of Edinburgh in 2006 and was designated by Time Magazine as one of the world's 100 most influential people in 2006. In 2007 Dr. Hansen won the Dan David Prize in the field of Quest for Energy, the Leo Szilard Award of the American Physical Society for Use of Physics for the Benefit of Society, and the American Association for the Advancement of Science Award for Scientific Freedom and Responsibility. In 2008, he won the Common Wealth Award for Distinguished Service in Science and was also awarded both the Ohio State University's Bownocker Medal and the Desert Research Institute's Nevada Medal. In 2009, Dr. Hansen received the American Meteorological Society's Carl-Gustaf Rossby Research Medal. In 2010 he received the Sophie Prize and the Blue Planet Prize.

Additional Information:
Http://www.columbia.edu/~jeh1/
http://www.columbia.edu/~mhs119/
Photos: http://ww.mediafire.com/?8ecel33ccmg81

Education:
BA with highest distinction (Physics and Mathematics), University of Iowa, 1963
MS (Astronomy), University of Iowa, 1965
Visiting student, Inst. of Astrophysics, University of Kyoto & Dept. of Astronomy, Tokyo University, Japan, 1965-1966
Ph.D. (Physics), University of Iowa, 1967

Research Interests:
Analysis of the causes and consequences of global climate change using the Earth's paleoclimate history, ongoing global observations, and interpretive tools including climate models. Connecting the dots all the way from climate observations to the policies that are needed to stabilize climate and preserve our planet for young people and other species.

Professional Employment:

1967-1969	NAS-NRC Resident Research Associate: Goddard Institute for Space Studies (GISS), NY
1969	NSF Postdoctoral Fellow: Leiden Observatory, Netherlands
1969-1972	Research Associate: Columbia University, NY
1972-1981	Staff Member/Space Scientist: Goddard Institute for Space Studies (GISS), Manager of GISS Planetary and Climate Programs
1978-1985	Adjunct Associate Professor: Department of Geological Sciences, Columbia University
1981-2013	Director: NASA Goddard Institute for Space Studies
1985-present	Adjunct Professor: Earth and Environmental Sciences, Columbia University
2013-present	Director: Program on Climate Science, Awareness and Solutions, Columbia University

Project Experience:

1971-1974	Co-Principal Investigator AEROPOL Project (airborne terrestrial infrared polarimeter)
1972-1985	Co-Investigator, Voyager Photopolarimeter Experiment
1974-1994	Principal Investigator (1974-8) and subsequently Co-Investigator, Pioneer Venus Orbiter Cloud-Photopolarimeter Experiment
1977-2000	Principal Investigator, Galileo (Jupiter Orbiter) Photopolarimeter Radiometer Experiment

Teaching Experience:
Atmospheric Radiation (graduate level): New York Univ., Dept. of Meteorology & Oceanography
Intro. to Planetary Atmospheres & Climate Change: Columbia Univ., Dept. of Geological Sciences

Awards:

1977	Goddard Special Achievement Award (Pioneer Venus)
1978	NASA Group Achievement Award (Voyager, Photopolarimeter)
1984	NASA Exceptional Service Medal (Radiative Transfer)
1989	National Wildlife Federation Conservation Achievement Award
1990	NASA Presidential Rank Award of Meritorious Executive
1991	University of Iowa Alumni Achievement Award
1992	American Geophysical Union Fellow
1993	NASA Group Achievement Award (Galileo, Polarimeter/Radiometer)
1996	Elected to National Academy of Sciences
1996	GSFC William Nordberg Achievement Medal
1996	Editors' Citation for Excellence in Refereeing for Geophysical Research Letters
1997	NASA Presidential Rank Award of Meritorious Executive
2000	University of Iowa Alumni Fellow
2000	GISS Best Scientific Publication (peer vote): "Global warming – alternative scenario"
2001	John Heinz Environment Award
2001	Roger Revelle Medal, American Geophysical Union
2004	GISS Best Scientific Publication (peer vote): 'Soot Climate Forcing'

2005	GISS Best Scientific Publication (peer vote): 'Earth's Energy Imbalance'
2006	Duke of Edinburgh Conservation Medal, World Wildlife Fund (WWF)
2006	GISS Best Scientific Publication (peer vote): 'Global Temperature Change'
2006	*Time Magazine* designation as one of World's 100 Most Influential People.
2007	Laureate, Dan David Prize for Outstanding Achievements & Impacts in Quest for Energy
2007	Leo Szilard Award, American Physical Society for Outstanding Promotion & Use of Physics for the Benefit of Society
2007	Haagen-Smit Clean Air Award
2008	American Association for the Advancement of Science Award for Scientific Freedom and Responsibility
2008	Nevada Medal, Desert Research Institute
2008	Common Wealth Award for Distinguished Service in Science
2008	Bownocker Medal, Ohio State University
2008	Rachel Carson Award for Integrity in Science, Center for Science in the Public Interest
2009	Carl-Gustaf Rossby Research Medal, American Meteorological Society
2009	Peter Berle Environmental Integrity Award
2010	Sophie Prize for Environmental and Sustainable Development
2010	Blue Planet Prize, Asahi Glass Foundation
2011	American Association of Physics Teachers Klopsteg Memorial Award for communicating physics to the general public
2011	Edinburgh Medal from City of Edinburgh, Edinburgh Science Festival
2012	Steve Schneider Climate Science Communications Award
2012	*Foreign Policy* designation as one of its Top 100 Global Thinkers
2013	Ridenhour Courage Prize
2013	NASA Distinguished Service Medal
2014	Center for International Environmental Law's Frederick R. Anderson Award for Outstanding Contributions to Addressing Climate Change
2014	Walker Prize, Museum of Science, Boston

Publications:

Hansen, J., Sato, M., Hearty, P., Ruedy, R., Kelley, M., Masson-Delmotte, V., Russell, G., Tselioudis, G., Cao, J., Rignot, E., Velicogna, I., Kandiano, E., von Schuckmann, K., Kharecha, P., Legrande, A. N., Bauer, M., and Lo, K.-W.: Ice melt, sea level rise and superstorms: evidence from paleoclimate data, climate modeling, and modern observations that 2 °C global warming is highly dangerous, Atmos. Chem. Phys. Discuss., 15, 20059-20179, doi:10.5194/acpd-15-20059-2015, 2015.

Hansen, J., 2014: Environment and Development Challenges: The Imperative of a Carbon Fee and Dividend. *The Oxford Handbook of the Macroeconomics of Global Warming*, chapter 26 (in press).

Nazarenko, L., G.A. Schmidt, R.L. Miller, N. Tausnev, M. Kelley, R. Ruedy, G.L. Russell, I. Aleinov, M. Bauer, S. Bauer, R. Bleck, V. Canuto, Y. Cheng, T.L. Clune, A.D. Del Genio, G. Faluvegi, J.E. Hansen, R.J. Healy, N.Y. Kiang, D. Koch, A.A. Lacis, A.N. LeGrande, J. Lerner, K.K. Lo, S. Menon, V. Oinas, J.P. Perlwitz, M.J. Puma, D. Rind, A. Romanou, M. Sato, D.T. Shindell, S. Sun, K. Tsigaridis, N. Unger, A. Voulgarakis, M.-S. Yao, and J. Zhang, 2014: Future climate change under RCP emission scenarios with GISS ModelE2. *J. Adv. Model. Earth Syst.*, submitted.

Hansen, J. 2014: The Energy to Fight Injustice. *Chemistry World*.

Miller, R.L., G.A. Schmidt, L.S. Nazarenko, N. Tausnev, S.E. Bauer, A.D. Del Genio, M. Kelley, K.K. Lo, R. Ruedy, D.T. Shindell, I. Aleinov, M. Bauer, R. Bleck, V. Canuto, Y.-H. Chen, Y. Cheng, T.L. Clune, G. Faluvegi, J.E. Hansen, R.J. Healy, N.Y. Kiang, D. Koch, A.A. Lacis, A.N. LeGrande, J. Lerner, S. Menon, V. Oinas, C. Pérez García-Pando, J.P. Perlwitz, M.J. Puma, D. Rind, A. Romanou, G.L. Russell, M. Sato, S. Sun, K. Tsigaridis, N. Unger, A. Voulgarakis, M. S. Yao, and J. Zhang, 2014: CMIP5 historical simulations (1850-2012) with GISS ModelE2. *J. Adv. Model. Earth Syst.*, **6**, no. 2, 441-477, doi:10.1002/2013MS000266.

Schmidt, G.A., M. Kelley, L. Nazarenko, R. Ruedy, G.L. Russell, I. Aleinov, M. Bauer, S.E. Bauer, M.K. Bhat, R. Bleck, V. Canuto, Y.-H. Chen, Y. Cheng, T.L. Clune, A. Del Genio, R. de Fainchtein, G. Faluvegi, J.E. Hansen, R.J. Healy, N.Y. Kiang, D. Koch, A.A. Lacis, A.N. LeGrande, J. Lerner, K.K. Lo, E.E. Matthews, S. Menon, R.L. Miller, V. Oinas, A.O. Oloso, J.P. Perlwitz, M.J. Puma, W.M. Putman, D. Rind, A. Romanou, M. Sato, D.T. Shindell, S. Sun, R.A. Syed, N. Tausnev, K. Tsigaridis, N. Unger, A. Voulgarakis, M.-S. Yao, and J. Zhang, 2014: Configuration and assessment of the GISS ModelE2 contributions to the CMIP5 archive. J. Adv. Model. Earth Syst., **6**, 141-184, doi:10.1002/2013MS000265.

Hansen, J., M. Sato, and R. Reudy, 2013: Reply to Rhines and Huybers: Changes in the frequency of extreme summer heat. *Proc. Natl. Acad. Sci*., **110**, E547-E548, doi:10.1073/pnas.1220916110.

Hansen, J., P. Kharecha, M. Sato, V. Masson-Delmotte, F. Ackerman, D. Beerling, P.J. Hearty, O. Hoegh-Guldberg, S.-L. Hsu, C. Parmesan, J. Rockstrom, E.J. Rohling, J. Sachs, P. Smith, K. Steffen, L. Van Susteren, K. von Schuckmann, and J.C. Zachos, 2013: Assessing "dangerous climate change": Required reduction of carbon emissions to protect young people, future generations and nature. *PLOS ONE*, **8**, e81648.

Hansen, J., M. Sato, and R. Ruedy, 2013: Reply to Stone et al.: Human-made role in local temperature extremes. *Proc. Natl. Acad. Sci.*, **110**, E1544, doi:10.1073/pnas.1301494110.

Kharecha, P., and J.E. Hansen, 2013: Response to comment by Rabilloud on "Prevented mortality and greenhouse gas emissions from historical and projected nuclear power". *Environ. Sci. Technol.*, **47**, 13900-13901, doi:10.1021/es404806w.

Kharecha, P.A., and J.E. Hansen, 2013: Response to comment on "Prevented mortality and greenhouse gas emissions from historical and projected nuclear power". *Environ. Sci. Technol.*, **47**, 6718-6719, doi:10.1021/es402211m.

Hansen, J., M. Sato, G. Russell, and P. Kharecha, 2013: Climate sensitivity, sea level, and atmospheric carbon dioxide, *Phil. Trans. Roy. Soc.* (in press).

Kharecha, P.A., and J.E. Hansen, 2013: Prevented mortality and greenhouse gas emissions from historical and projected nuclear power. *Environ. Sci. Technol.*, **47**, 4889-4895, doi:10.1021/es3051197

Hansen, J., P. P. Kharecha, and M. Sato, 2013: Climate forcing growth rates: Doubling down on our Faustian bargain. *Environ. Res. Lett.*, 8, 011006, doi:10.1088/1748-9326/8/1/011006.

Lacis, A.A., J.E. Hansen, G.L. Russell, V. Oinas, and J. Jonas, 2013: The role of long-lived greenhouse gases as principal LW control knob that governs the global surface temperature for past and future climate change. *Tellus B*, **65**, 19734, doi:10.3402/tellusb.v65i0.19734

Previdi, M., B.G. Liepert, D. Peteet, J. Hansen, D.J. Beerling, A.J. Broccoli, S. Frolking, J.N. Galloway, M. Heimann, C. Le Quéré, S. Levitus, and V. Ramaswamy, 2013: Climate sensitivity in the Anthropocene. *Q. J. R. Meteorol. Soc.*, **139**, 1121-1131, doi:10.1002/qj.2165.

Rohling, E.J., A. Sluijs, H.A. Dijkstra, P. Köhler, R.S.W. van de Wal, A.S. von der Heydt, D.J. Beerling, A. Berger, P.K. Bijl, M. Crucifix, R. DeConto, S.S. Drijfhout, A. Fedorov, G.L. Foster, A. Ganopolski, J. Hansen, B. Hönisch, H. Hooghiemstra, M. Huber, P. Huybers, R. Knutti, D.W. Lea, L.J. Lourens, D. Lunt, V. Masson-Demotte, M. Medina-Elizalde, B. Otto-Bliesner, M. Pagani, H. Pälike, H. Renssen, D.L. Royer, M. Siddall, P. Valdes, J.C. Zachos, and R.E. Zeebe, 2012: Making sense of palaeoclimate sensitivity. *Nature*, **491**, 683-691, doi:10.1038/nature11574.

Hansen, J., M. Sato, and R. Ruedy, 2012: Perception of climate change. *Proc. Natl. Acad. Sci.*, **109**, 14726-14727, E2415-E2423, doi:10.1073/pnas.1205276109.

Hansen, J.E., and M. Sato, 2012: Paleoclimate implications for human-made climate change. In *Climate Change:Inferences from Paleoclimate and Regional Aspects*. A. Berger, F. Mesinger, and D. Šijački, Eds. Springer, pp. 21- 48, doi:10.1007/978-3-7091-0973-1_2.

Hansen, J., M. Sato, P. Kharecha, and K. von Schuckmann, 2011: Earth's energy imbalance and implications. *Atmos. Chem. Phys.*, **11**, 13421-13449, doi:10.5194/acp-11-13421-2011.

Kharecha, P.A., C.F. Kutscher, J.E. Hansen, and E. Mazria, 2010: Options for near-term phaseout of CO2 emissions from coal use in the United States. *Environ. Sci. Technol.*, 44, 4050-4062, doi:10.1021/es903884a.

Hansen, J., R. Ruedy, M. Sato, and K. Lo, 2010: Global surface temperature change. *Rev. Geophys.*, 48, RG4004, doi:10.1029/2010RG000345.

Masson-Delmotte, V., B. Stenni, K. Pol, P. Braconnot, O. Cattani, S. Falourd, M. Kageyama, J. Jouzel, A. Landais, B. Minster, J.M. Barnola, J. Chappellaz, G. Krinner, S. Johnsen, R. Röthlisberger, J. Hansen, U. Mikolajewicz, and B. Otto-Bliesner, 2010: EPICA Dome C record of glacial and interglacial intensities. *Quat. Sci. Rev.*, **29**, 113-128, doi:10.1016/j.quascirev.2009.09.030.

Rockström, J., W. Steffen, K. Noone, Å. Persson, F.S. Chapin, III, E. Lambin, T.M. Lenton, M. Scheffer, C. Folke, H. Schellnhuber, B. Nykvist, C.A. De Wit, T. Hughes, S. van der Leeuw, H. Rodhe, S. Sörlin, P.K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R.W. Corell, V.J. Fabry, J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen, and J. Foley, 2009: Planetary boundaries: Exploring the safe operating space for humanity. *Ecol. Soc.*, **14** (2), 32.

Rockström, J., W. Steffen, K. Noone, Å. Persson, F.S. Chapin, III, E.F. Lambin, T.M. Lenton, M. Scheffer, C. Folke, H.J. Schellnhuber, B. Nykvist, C.A. de Wit, T. Hughes, S. van der Leeuw, H. Rodhe, S. Sörlin, P.K. Snyder, R. Costanza, U. Svedin, M. Falkenmark, L. Karlberg, R.W. Corell, V.J. Fabry, J. Hansen, B. Walker, D. Liverman, K. Richardson, P. Crutzen, and J.A. Foley, 2009: A safe operating space for humanity. *Nature*, **461**, 472-475, doi:10.1038/461472a.

Xu, B., J. Cao, J. Hansen, T. Yao, D.J. Joswia, N. Wang, G. Wu, M. Wang, H. Zhao, W. Yang, X. Liu, and J. He, 2009: Black soot and the survival of Tibetan glaciers. *Proc. Natl. Acad. Sci.*, **106** , 22114-22118, doi:10.1073/pnas.0910444106.

Hansen, J., Mki. Sato, P. Kharecha, D. Beerling, R. Berner, V. Masson-Delmotte, M. Pagani, M. Raymo, D.L. Royer, and J.C. Zachos, 2008: Target atmospheric CO_2: Where should humanity aim? *Open Atmos. Sci. J.*, **2**, 217-231, doi:10.2174/1874282300802010217.

Kharecha, P.A., and J.E. Hansen, 2008: Implications of "peak oil" for atmospheric CO_2 and climate. *Global Biogeochem. Cycles*, **22**, GB3012, doi:10.1029/2007GB003142.

Hansen, J., 2008: Tipping Point: Perspective of a Climatologist. In *The State of the Wild: A Global Portrait of Wildlife, Wild Lands, and Oceans.* E. Fearn, Ed. Wildlife Conservation Society/Island Press, pp. 6-15.

Hansen, J.E., 2007: Scientific reticence and sea level rise. *Environ. Res. Lett.*, **2**, 024002, doi:10.1088/1748-9326/2/2/024002.

Hansen, J., Mki. Sato, R. Ruedy, and 44 co-authors, 2007: Climate simulations for 1880-2003 with GISS modelE. *Clim. Dynam.*, **29**, 661-696, doi:10.1007/s00382-007-0255-8.

Hansen, J., 2007: Climate catastrophe. *New Scientist*, **195**, no. 2614 (July 28), 30-34.

Hansen, J., 2007: Why we can't wait: A 5-step plan for solving the global crisis. *Nation*, **284**, no. 18 (May 7), 13-14.

Hansen, J., Mki. Sato, P. Kharecha, G. Russell, D.W. Lea, and M. Siddall, 2007: Climate change and trace gases. *Phil. Trans. Royal. Soc. A*, **365**, 1925-1954, doi:10.1098/rsta.2007.2052.

Hansen, J., Mki. Sato, R. Ruedy, and 44 co-authors, 2007: Dangerous human-made interference with climate: A GISS modelE study. *Atmos. Chem. Phys.*, **7**, 2287-2312.

Hansen, J.E., 2007: Scientific reticence and sea level rise. *Environ. Res. Lett.*, **2**, 024002, doi:10.1088/17489326/2/2/024002.

Nazarenko, L., N. Tausnev, and J. Hansen, 2007: The North Atlantic thermohaline circulation simulated by the GISS climate model during 1970-99. *Atmos.-Ocean*, **45**, 81-92, doi:10.3137/ao.450202.

Mishchenko, M.I., B. Cairns, G. Kopp, C.F. Schueler, B.A. Fafaul, J.E. Hansen, R.J. Hooker, T. Itchkawich, H.B. Maring, and L.D. Travis, 2007: Precise and accurate monitoring of terrestrial aerosols and total solar irradiance: Introducing the Glory mission. *Bull. Amer. Meteorol. Soc.*, **88**, 677-691, doi:10.1175/BAMS-88-5-677.

Novakov, T., S. Menon, T.W. Kirchstetter, D. Koch, and J.E. Hansen, 2007: Reply to comment by R. L. Tanner and D. J.Eatough on "Aerosol organic carbon to black carbon ratios: Analysis of published data and implications for climate forcing". *J. Geophys. Res.*, **112**, D02203, doi:10.1029/2006JD007941.

Rahmstorf, S., A. Cazenave, J.A. Church, J.E. Hansen, R.F. Keeling, D.E. Parker, and R.C.J. Somerville, 2007: Recent climate observations compared to projections. *Science*, **316**, 709, doi:10.1126/science.1136843.

Hansen, J., 2006: The threat to the planet. *New York Rev. Books*, **53**, no. 12 (July 13, 2006), 12-16.

Hansen, J., Mki. Sato, R. Ruedy, K. Lo, D.W. Lea, and M. Medina-Elizade, 2006: Global temperature change. *Proc. Natl. Acad. Sci.*, **103**, 14288-14293, doi:10.1073/pnas.0606291103.

Nazarenko, L., N. Tausnev, and J. Hansen, 2006: Sea-ice and North Atlantic climate response to CO_2-induced warming and cooling conditions. *J. Glaciol.*, **52**, 433-439.

Santer, B.D., T.M.L. Wigley, P.J. Gleckler, C. Bonfils, M.F. Wehner, K. AchutaRao, T.P. Barnett, J.S. Boyle, W. Brüggemann, M. Fiorino, N. Gillett, J.E. Hansen, P.D. Jones, S.A. Klein, G.A. Meehl, S.C.B. Raper, R.W. Reynolds, K.E. Taylor, and W.M. Washington, 2006: Forced and unforced ocean temperature changes in Atlantic and Pacific tropical cyclogenesis regions. *Proc. Natl. Acad. Sci.*, **103**, 13905-13910, doi:10.1073/pnas.0602861103.

Schmidt, G.A., R. Ruedy, J.E. Hansen, I. Aleinov, N. Bell, M. Bauer, S. Bauer, B. Cairns, V. Canuto, Y. Cheng, A. Del Genio, G. Faluvegi, A.D. Friend, T.M. Hall, Y. Hu, M. Kelley, N.Y. Kiang, D. Koch, A.A. Lacis, J. Lerner, K.K. Lo, R.L. Miller, L. Nazarenko, V. Oinas, Ja. Perlwitz, Ju. Perlwitz, D. Rind, A. Romanou, G.L. Russell, Mki. Sato, D.T. Shindell, P.H. Stone, S. Sun, N. Tausnev, D. Thresher, and M.-S. Yao, 2006: Present day atmospheric simulations using GISS ModelE: Comparison to in-situ, satellite and reanalysis data. *J. Climate*, **19**, 153-192, doi:10.1175/JCLI3612.1.

Shindell, D., G. Faluvegi, A. Lacis, J. Hansen, R. Ruedy, and E. Aguilar, 2006: Role of tropospheric ozone increases in 20th century climate change. *J. Geophys. Res.*, **111**, D08302, doi:10.1029/2005JD006348.

Shindell, D.T., G. Faluvegi, R.L. Miller, G.A. Schmidt, J.E. Hansen, and S. Sun, 2006: Solar and anthropogenic forcing of tropical hydrology. *Geophys. Res. Lett.*, **33**, L24706, doi:10.1029/2006GL027468, 2006.

Hansen, J., L. Nazarenko, R. Ruedy, Mki. Sato, and 11 co-authors, 2005: Earth's energy imbalance: Confirmation and implications. *Science*, **308**, 1431-1435, doi:10.1126/science.1110252.

Hansen, J., Mki. Sato, R. Ruedy, L. Nazarenko, A. Lacis, G.A. Schmidt, G. Russell, and 38 co-authors, 2005: Efficacy of climate forcings. *J. Geophys. Res.*, **110**, D18104, doi:10.1029/2005JD005776.

Hansen, J.E., 2005: A slippery slope: How much global warming constitutes "dangerous anthropogenic interference"? An editorial essay. *Climatic Change*, **68**, 269-279, doi:10.1007/s10584-005-4135-0.

Koch, D., and J. Hansen, 2005: Distant origins of Arctic black carbon: A Goddard Institute for Space Studies ModelE experiment. *J. Geophys. Res.*, **110**, D04204, doi:10.1029/2004JD005296.

Novakov, T., S. Menon, T.W. Kirchstetter, D. Koch, and J.E. Hansen, 2005: Aerosol organic carbon to black carbon ratios: Analysis of published data and implications for climate forcing. *J. Geophys. Res.*, **110**, D21205, doi:10.1029/2005JD005977.

Santer, B.D., T.M.L. Wigley, C. Mears, F.J. Wentz, S.A. Klein, D.J. Seidel, K.E. Taylor, P.W. Thorne, M.F. Wehner, P.J. Gleckler, J.S. Boyle, W.D. Collins, K.W. Dixon, C. Doutriaux, M. Free, Q. Fu, J.E. Hansen, and 8 co-authors, 2005: Amplification of surface temperature trends and variability in the tropical atmosphere. *Science*, **309**, 1551-1556, doi:10.1126/science.1114867.

Hansen, J., 2004: Defusing the global warming time bomb. *Sci. Amer.*, **290**, no. 3, 68-77.

Hansen, J., T. Bond, B. Cairns, H. Gaeggler, B. Liepert, T. Novakov, and B. Schichtel, 2004: Carbonaceous aerosols in the industrial era. *Eos Trans. Amer. Geophys. Union*, **85**, no. 25, 241, 245.

Hansen, J., and L. Nazarenko, 2004: Soot climate forcing via snow and ice albedos. *Proc. Natl. Acad. Sci.*, **101**, 423-428, doi:10.1073/pnas.2237157100.

Hansen, J., and Mki. Sato, 2004: Greenhouse gas growth rates. *Proc. Natl. Acad. Sci.*, **101**, 16109-16114, doi:10.1073/pnas.0406982101.

Mishchenko, M.I., B. Cairns, J.E. Hansen, L.D. Travis, R. Burg, Y.J. Kaufman, J.V. Martins, and E.P. Shettle, 2004: Monitoring of aerosol forcing of climate from space: Analysis of measurement requirements. *J. Quant. Spectrosc. Radiat. Transfer*, **88**, 149-161, doi:10.1016/j.jqsrt.2004.03.030.

Novakov, T., and J.E. Hansen, 2004: Black carbon emissions in the United Kingdom during the past four decades: An empirical analysis. *Atmos. Environ.*, **38**, 4155-4163, doi:10.1016/j.atmosenv.2004.04.031.

Hansen, J., 2003: Can we defuse the global warming time bomb? *naturalScience*, posted Aug. 1, 2003.

Novakov, T., V. Ramanathan, J.E. Hansen, T.W. Kirchstetter, Mki. Sato, J.E. Sinton, and J.A. Satahye, 2003: Large historical changes of fossil-fuel black carbon aerosols. *Geophys. Res. Lett.*, **30**, no. 6, 1324, doi:10.1029/2002GL016345

Santer, B.D., R. Sausen, T.M.L. Wigley, J.S. Boyle, K. AchutaRao, C. Doutriaux, J.E. Hansen, G.A. Meehl, E. Roeckner, R. Ruedy, G. Schmidt, and K.E. Taylor, 2003: Behavior of tropopause height and atmospheric temperature in models, reanalyses, and observations: Decadal changes. *J. Geophys. Res.*, **108**, no. D1, 4002, doi:10.1029/2002JD002258.

Sato, Mki., J. Hansen, D. Koch, A. Lacis, R. Ruedy, O. Dubovik, B. Holben, M. Chin, and T. Novakov, 2003: Global atmospheric black carbon inferred from AERONET. *Proc. Natl. Acad. Sci.*, **100**, 6319-6324, doi:10.1073/pnas.0731897100.

Sun, S., and J.E. Hansen, 2003: Climate simulations for 1951-2050 with a coupled atmosphere-ocean model. *J. Climate*, **16**, 2807-2826, doi:10.1175/1520-0442(2003)016<2807:CSFWAC>2.0.CO;2.

Carmichael, G.R., D.G. Streets, G. Calori, M. Amann, M.Z. Jacobson, J. Hansen, and H. Ueda, 2002: Changing trends in sulfur emissions in Asia: Implications for acid deposition. *Environ. Sci. Tech*, **36**, 4707-4713, doi:10.1021/es011509c.

Hansen, J., R. Ruedy, Mki. Sato, and K. Lo, 2002: Global warming continues. *Science*, **295**, 275, doi:10.1126/science.295.5553.275c.

Hansen, J., Mki. Sato, L. Nazarenko, R. Ruedy, A. Lacis, D. Koch, I. Tegen, T. Hall,and 20 co-authors, 2002: Climate forcings in Goddard Institute for Space Studies SI2000 simulations. *J. Geophys. Res.*, **107**, no. D18, 4347, doi:10.1029/2001JD001143.

Hansen, J.E. (Ed.), 2002: *Air Pollution as a Climate Forcing: A Workshop*. NASA Goddard Institute for Space Studies.

Hansen, J.E., 2002: A brighter future. *Climatic Change*, **52**, 435-440, doi:10.1023/A:1014226429221

Menon, S., J.E. Hansen, L. Nazarenko, and Y. Luo, 2002: Climate effects of black carbon aerosols in China and India. *Science*,**297**, 2250-2253, doi:10.1126/science.1075159.

Robinson, W.A., R. Ruedy, and J.E. Hansen, 2002: General circulation model simulations of recent cooling in the east–central United States. *J. Geophys. Res.*, **107**, no. D24, 4748, doi:10.1029/2001JD001577.

Hansen, J.E., R. Ruedy, Mki. Sato, M. Imhoff, W. Lawrence, D. Easterling, T. Peterson, and T. Karl, 2001: A closer look at United States and global surface temperature change. *J. Geophys. Res.*, **106**, 23947-23963, doi:10.1029/2001JD000354.

Hansen, J.E., and Mki. Sato, 2001: Trends of measured climate forcing agents. *Proc. Natl. Acad. Sci.*, **98**, 14778-14783, doi:10.1073/pnas.261553698.

Nazarenko, L., J. Hansen, N. Tausnev, and R. Ruedy, 2001: Response of the Northern Hemisphere sea ice to greenhouse forcing in a global climate model. *Ann. Glaciol.*, **33**, 513-520.

Oinas, V., A.A. Lacis, D. Rind, D.T. Shindell, and J.E. Hansen, 2001: Radiative cooling by stratospheric water vapor: Big differences in GCM results. *Geophys. Res. Lett.*, **28**, 2791-2794, doi:10.1029/2001GL013137.

Santer, B.D., T.M.L. Wigley, C. Doutriaux, J.S. Boyle, J.E. Hansen, P.D. Jones, G.A. Meehl, E. Roeckner, S. Sengupta, and K.E. Taylor, 2001: Accounting for the effects of volcanoes and ENSO in comparisons of modeled and observed temperature trends. *J. Geophys. Res.*, **106**, 28033-28059, doi:10.1029/2000JD000189.

Streets, D.G., K. Jiang, X. Hu, J.E. Sinton, X.-Q. Zhang, D. Xu, M.Z. Jacobson, and J.E. Hansen, 2001: Recent reductions in China's greenhouse gas emissions. *Science*, **294**, 1835-1837, doi:10.1126/science.1065226.

Hansen, J., R. Ruedy, A. Lacis, Mki. Sato, L. Nazarenko, N. Tausnev, I. Tegen, and D. Koch, 2000: Climate modeling in the global warming debate. In *General Circulation Model Development*. D. Randall, Ed. Academic Press, pp. 127-164.

Hansen, J., Mki. Sato, R. Ruedy, A. Lacis, and V. Oinas, 2000: Global warming in the twenty-first century: An alternative scenario. *Proc. Natl. Acad. Sci.*, **97**, 9875-9880, doi:10.1073/pnas.170278997.

Hansen, J.E., 2000: The Sun's role in long-term climate change. *Space Sci. Rev.*, **94**, 349-356, doi:10.1023/A:1026748129347.

Lacis, A.A., B.E. Carlson, and J.E. Hansen, 2000: Retrieval of atmospheric NO_2, O_3, aerosol optical depth, effective radius and variance information from SAGE II multi-spectral extinction measurements. *Appl. Math. Comput.*, **116**, 133-151, doi:10.1016/S0096-3003(99)00200-3.

Hansen, J., R. Ruedy, J. Glascoe, and Mki. Sato, 1999: GISS analysis of surface temperature change. *J. Geophys. Res.*, **104**, 30997-31022, doi:10.1029/1999JD900835.

Hansen, J., Mki. Sato, J. Glascoe, and R. Ruedy, 1998: A common sense climate index: Is climate changing noticeably? *Proc. Natl. Acad. Sci.*, **95**, 4113-4120.

Hansen, J., Mki. Sato, A. Lacis, R. Ruedy, I. Tegen, and E. Matthews, 1998: Perspective: Climate forcings in the industrial era. *Proc. Natl. Acad. Sci.*, **95**, 12753-12758.

Hansen, J.E., 1998: Book review of Sir John Houghton's *Global Warming: The Complete Briefing*. *J. Atmos. Chem.*, **30**, 409-412.

Hansen, J.E., Mki. Sato, R. Ruedy, A. Lacis, and J. Glascoe, 1998: Global climate data and models: A reconciliation. *Science*, **281**, 930-932, doi:10.1126/science.281.5379.930.

Matthews, E., and J. Hansen (Eds.), 1998: *Land Surface Modeling: A Mini-Workshop*. NASA Goddard Institute for Space Studies.

Hansen, J., C. Harris, C. Borenstein, B. Curran, and M. Fox, 1997: Research education. *J. Geophys. Res.*, **102**, 25677-25678, doi:10.1029/97JD02172.

Hansen, J., R. Ruedy, A. Lacis, G. Russell, Mki. Sato, J. Lerner, D. Rind, and P. Stone, 1997: Wonderland climate model. *J. Geophys. Res.*, **102**, 6823-6830, doi:10.1029/96JD03435.

Hansen, J., Mki. Sato, A. Lacis, and R. Ruedy, 1997: The missing climate forcing. *Phil. Trans. Royal Soc. London B*, **352**, 231-240.

Hansen, J., Mki. Sato, and R. Ruedy, 1997: Radiative forcing and climate response. *J. Geophys. Res.*, **102**, 6831-6864, doi:10.1029/96JD03436.

Hansen, J., Mki. Sato, R. Ruedy, A. Lacis, K. Asamoah, K. Beckford, S. Borenstein, E. Brown, B. Cairns, B. Carlson, B. Curran, S. de Castro, L. Druyan, P. Etwarrow, T. Ferede, M. Fox, D. Gaffen, J. Glascoe, H. Gordon, S. Hollandsworth, X. Jiang, C. Johnson, N. Lawrence, J. Lean, J. Lerner, K. Lo, J. Logan, A. Luckett, M.P. McCormick, R. McPeters, R.L. Miller, P. Minnis, I. Ramberran, G. Russell, P. Russell, P. Stone, I. Tegen, S. Thomas, L. Thomason, A. Thompson, J. Wilder, R. Willson, and J. Zawodny, 1997: Forcings and chaos in interannual to decadal climate change. *J. Geophys. Res.*, **102**, 25679-25720, doi:10.1029/97JD01495.

Hansen, J., R. Ruedy, Mki. Sato, and R. Reynolds, 1996: Global surface air temperature in 1995: Return to pre-Pinatubo level. *Geophys. Res. Lett.*, **23**, 1665-1668, doi:10.1029/96GL01040.

Hansen, J., Mki. Sato, R. Ruedy, A. Lacis, K. Asamoah, S. Borenstein, E. Brown, B. Cairns, G. Caliri, M. Campbell, B. Curran, S. de Castro, L. Druyan, M. Fox, C. Johnson, J. Lerner, M.P. McCormick, R.L. Miller, P. Minnis, A. Morrison, L. Pandolfo, I. Ramberran, F. Zaucker, M. Robinson, P. Russell, K. Shah, P. Stone, I. Tegen, L. Thomason, J. Wilder, and H. Wilson, 1996: A Pinatubo climate modeling investigation. In *The Mount Pinatubo Eruption: Effects on the Atmosphere and Climate*, NATO ASI Series Vol. I 42. G. Fiocco, D. Fua, and G. Visconti, Eds. Springer-Verlag, pp. 233-272.

Hansen, J., W. Rossow, B. Carlson, A. Lacis, L. Travis, A. Del Genio, I. Fung, B. Cairns, M. Mishchenko, and Mki. Sato, 1995: Low-cost long-term monitoring of global climate forcings and feedbacks. *Climatic Change*, **31**, 247-271, doi:10.1007/BF01095149.

Hansen, J., Mki. Sato, and R. Ruedy, 1995: Long-term changes of the diurnal temperature cycle: Implications about mechanisms of global climate change. *Atmos. Res.*, **37**, 175-209, doi:10.1016/0169-8095(94)00077-Q.

Hansen, J., H. Wilson, Mki. Sato, R. Ruedy, K. Shah, and E. Hansen, 1995: Satellite and surface temperature data at odds? *Climatic Change*, **30**, 103-117, doi:10.1007/BF01093228.

Hansen, J., 1993: Climate forcings and feedbacks. In *Long-Term Monitoring of Global Climate Forcings and Feedbacks*, NASA CP-3234. J. Hansen, W. Rossow, and I. Fung, Eds. National Aeronautics and Space Administration, pp. 6-12.

Hansen, J., 1993: Climsat rationale. In *Long-Term Monitoring of Global Climate Forcings and Feedbacks*, NASA CP-3234. J. Hansen, W. Rossow, and I. Fung, Eds. National Aeronautics and Space Administration, pp. 26-35.

Hansen, J., A. Lacis, R. Ruedy, Mki. Sato, and H. Wilson, 1993: How sensitive is the world's climate? *Natl. Geog. Soc. Res. Exploration*, **9**, 142-158.
Hansen, J., W. Rossow, and I. Fung (Eds.), 1993: *Long-Term Monitoring of Global Climate Forcings and Feedbacks.* NASA CP-3234. National Aeronautics and Space Administration.
Hansen, J., and H. Wilson, 1993: Commentary on the significance of global temperature records. *Climatic Change*, **25**, 185-191, doi:10.1007/BF01661206.
Pollack, J.B., D. Rind, A. Lacis, J.E. Hansen, Mki. Sato, and R. Ruedy, 1993: GCM simulations of volcanic aerosol forcing. Part I: Climate changes induced by steady-state perturbations. *J. Climate*, **6**, 1719-1742, doi:10.1175/1520-0442(1993)006<1719:GSOVAF>2.0.CO;2.
Sato, Mki., J.E. Hansen, M.P. McCormick, and J.B. Pollack, 1993: Stratospheric aerosol optical depths, 1850-1990. *J. Geophys. Res.*, **98**, 22987-22994, doi:10.1029/93JD02553.
Charlson, R.J., S.E. Schwartz, J.M. Hales, R.D. Cess, J.A. Coakley, Jr., J.E. Hansen, and D.J. Hoffman, 1992: Climate forcing by anthropogenic aerosols. *Science*, **255**, 423-430, doi:10.1126/science.255.5043.423.
Hansen, J., A. Lacis, R. Ruedy, and Mki. Sato, 1992: Potential climate impact of Mount Pinatubo eruption. *Geophys. Res. Lett.*, **19**, 215-218, doi:10.1029/91GL02788.
Lacis, A., J. Hansen, and Mki. Sato, 1992: Climate forcing by stratospheric aerosols. *Geophys. Res. Lett.*, **19**, 1607-1610, doi:10.1029/92GL01620.
Hansen, J.E., and A. Lacis, 1991: Sun and water in the greenhouse: Reply to comments. *Nature*, **349**, 467, doi:10.1038/349467c0.
Hansen, J., D. Rind, A. Del Genio, A. Lacis, S. Lebedeff, M. Prather, R. Ruedy, and T. Karl, 1991: Regional greenhouse climate effects. In *Greenhouse-Gas-Induced Climatic Change: A Critical Appraisal of Simulations and Observations*. M.E. Schlesinger, Ed. Elsevier, pp. 211-229.
Hansen, J., W. Rossow, and I. Fung, 1990: The missing data on global climate change. *Issues Sci. Technol.*, **7**, 62-69.
Hansen, J.E., and A.A. Lacis, 1990: Sun and dust versus greenhouse gases: An assessment of their relative roles in global climate change. *Nature*, **346**, 713-719, doi:10.1038/346713a0.
Hansen, J.E., A.A. Lacis, and R.A. Ruedy, 1990: Comparison of solar and other influences on long-term climate. In *Climate Impact of Solar Variability*, NASA CP-3086. K.H. Schatten and A. Arking, Eds. National Aeronautics and Space Administration, pp. 135-145.
Lorius, C., J. Jouzel, D. Raynaud, J. Hansen, and H. Le Treut, 1990: The ice-core record: Climate sensitivity and future greenhouse warming. *Nature*, **347**, 139-145, doi:10.1038/347139a0.
Rind, D., R. Goldberg, J. Hansen, C. Rosenzweig, and R. Ruedy, 1990: Potential evapotranspiration and the likelihood of future drought. *J. Geophys. Res.*, **95**, 9983-10004.
Hansen, J., A. Lacis, and M. Prather, 1989: Greenhouse effect of chlorofluorocarbons and other trace gases. *J. Geophys. Res.*, **94**, 16417-16421.
Hansen, J., D. Rind, A. Del Genio, A. Lacis, S. Lebedeff, M. Prather, R. Ruedy, and T. Karl, 1989: Regional greenhouse climate effects. In *Coping with Climatic Change: Proceedings of the Second North American Conference on Preparing for Climate Change*. J.C. Topping, Jr., Ed. The Climate Institute.
Hansen, J., I. Fung, A. Lacis, D. Rind, Lebedeff, R. Ruedy, G. Russell, and P. Stone, 1988: Global climate changes as forecast by Goddard Institute for Space Studies three-dimensional model. *J. Geophys. Res.*, **93**, 9341-9364, doi:10.1029/88JD00231.
Hansen, J., and S. Lebedeff, 1988: Global surface air temperatures: Update through 1987. *Geophys. Res. Lett.*, **15**, 323-326, doi:10.1029/88GL02067.
Hansen, J.E., and S. Lebedeff, 1987: Global trends of measured surface air temperature. *J. Geophys. Res.*, **92**, 13345-13372.
Ramanathan, V., L. Callis, R. Cess, J. Hansen, I. Isaksen, W. Kuhn, A. Lacis, F. Luther, J. Mahlman, R. Reck, and M. Schlesinger, 1987: Climate-chemical interactions and effects of changing atmospheric trace gases. *Rev. Geophys.*, **25**, 1441-1482.
Hunten, D.M., L. Colin, and J.E. Hansen, 1986: Atmospheric science on the Galileo mission. *Space Sci. Rev.*, **44**, 191-240, doi:10.1007/BF00200817.
Hansen, J.E., 1985: Geophysics: Global sea level trends. *Nature*, **313**, 349-350.
Bennett, T., W. Broecker, and J. Hansen (Eds.), 1985: *North Atlantic Deep Water Formation*. NASA CP-2367. National Aeronautics and Space Administration.
Hansen, J., G. Russell, A. Lacis, I. Fung, D Rind, and P. Stone, 1985: Climate response times: Dependence on climate sensitivity and ocean mixing. *Science*, **229**, 857-859, doi:10.1126/science.229.4716.857.
Hansen, J., A. Lacis, and D. Rind, 1984: Climate trends due to increasing greenhouse gases. In *Proceedings of the Third Symposium on Coastal and Ocean Management, ASCE/San Diego, California, June 1-4, 1983*, pp. 2796-2810.

Hansen, J., A. Lacis, D. Rind, G. Russell, P. Stone, I. Fung, R. Ruedy, and J. Lerner, 1984: Climate sensitivity: Analysis of feedback mechanisms. In *Climate Processes and Climate Sensitivity*, AGU Geophysical Monograph 29, Maurice Ewing Vol. 5. J.E. Hansen and T. Takahashi, Eds. American Geophysical Union, pp. 130-163.

Hansen, J.E., and T. Takahashi (Eds.), 1984: *Climate Processes and Climate Sensitivity*. AGU Geophysical Monograph 29, Maurice Ewing Vol. 5. American Geophysical Union.

Rind, D., R. Suozzo, A. Lacis, G. Russell, and J. Hansen, 1984: *21 Layer Troposphere-Stratosphere Climate Model*. NASA TM-86183. National Aeronautics and Space Administration.

Hansen, J., V. Gornitz, S. Lebedeff, and E. Moore, 1983: Global mean sea level: Indicator of climate change? *Science*, **219**, 997.

Hansen, J., G. Russell, D. Rind, P. Stone, A. Lacis, S. Lebedeff, R. Ruedy, and L. Travis, 1983: Efficient three-dimensional global models for climate studies: Models I and II. *M. Weather Rev.*, **111**, 609-662, doi:10.1175/1520-0493(1983)111<0609:ETDGMF>2.0.CO;2.

Hansen, J., D. Johnson, A. Lacis, S. Lebedeff, P. Lee, D. Rind, and G. Russell, 1983: Climatic effects of atmospheric carbon dioxide. *Science*, **220**, 874-875, doi:10.1126/science.220.4599.874-a.

Pinto, J.P., D. Rind, G.L. Russell, J.A. Lerner, J.E. Hansen, Y.L. Yung, and S. Hameed, 1983: A general circulation model study of atmospheric carbon monoxide. *J. Geophys. Res.*, **88**, 3691-3702.

Gornitz, V., S. Lebedeff, and J. Hansen, 1982: Global sea level trend in the past century. *Science*, **215**, 1611-1614, doi:10.1126/science.215.4540.1611.

Hansen, J., D. Johnson, A. Lacis, S. Lebedeff, P. Lee, D. Rind, and G. Russell, 1981: Climate impact of increasing atmospheric carbon dioxide. *Science*, **213**, 957-966, doi:10.1126/science.213.4511.957.

Lacis, A., J. Hansen, P. Lee, T. Mitchell, and S. Lebedeff, 1981: Greenhouse effect of trace gases, 1970-1980. *Geophys. Res. Lett.*, **8**, 1035-1038.

Hansen, J., 1980: Book review of *Theory of Planetary Atmospheres* by J.W. Chamberlain. *Icarus*, **41**, 175-176.

Hansen, J.E., A.A. Lacis, P. Lee, and W.-C. Wang, 1980: Climatic effects of atmospheric aerosols. *Ann. New York Acad. Sciences*, **338**, 575-587.

Kawabata, K., D.L. Coffeen, J.E. Hansen, W.A. Lane, Mko. Sato, and L.D. Travis, 1980: Cloud and haze properties from Pioneer Venus polarimetry. *J. Geophys. Res.*, **85**, 8129-8140.

Sato, Mki., and J.E. Hansen, 1979: Jupiter's atmospheric composition and cloud structure deduced from absorption bands in reflected sunlight. *J. Atmos. Sci.*, **36**, 1133-1167, doi:10.1175/1520-0469(1979)036<1133:JACACS>2.0.CO;2

Travis, L.D., D.L. Coffeen, A.D. Del Genio, J.E. Hansen, K. Kawabata, A.A. Lacis, W.A. Lane, S.A. Limaye, W.B. Rossow, and P.H. Stone, 1979: Cloud images from the Pioneer Venus orbiter. *Science*, **205**, 74-76, doi:10.1126/science.205.4401.74.

Travis, L.D., D.L. Coffeen, J.E. Hansen, K. Kawabata, A.A. Lacis, W.A. Lane, S.A. Limaye, and P.H. Stone, 1979: Orbiter cloud photopolarimeter investigation. *Science*, **203**, 781-785, doi:10.1126/science.203.4382.781.

Hansen, J.E., W.-C. Wang, and A.A. Lacis, 1978: Mount Agung eruption provides test of a global climatic perturbation. *Science*, **199**, 1065-1068, doi:10.1126/science.199.4333.1065.

Knollenberg, R.G., J. Hansen, B. Ragent, J. Martonchik, and M. Tomasko, 1977: The clouds of Venus. *Space Sci. Rev.*, **20**, 329-354, doi:10.1007/BF02186469.

Lillie, C.F., C.W. Hord, K. Pang, D.L. Coffeen, and J.E. Hansen, 1977: The Voyager mission Photopolarimeter Experiment. *Space Sci. Rev.*, **21**, 159-181, doi:10.1007/BF00200849.

Sato, Mki., K. Kawabata, and J.E. Hansen, 1977: A fast invariant imbedding method for multiple scattering calculations and an application to equivalent widths of CO_2 lines on Venus. *Astrophys. J.*, **216**, 947-962.

Schubert, G., C.C. Counselman, III, J. Hansen, S.S. Limaye, G. Pettengill, A. Seiff, I.I. Shapiro, V.E. Suomi, F. Taylor, L. Travis, R. Woo, and R.E. Young, 1977: Dynamics, winds, circulation and turbulence in the atmosphere of Venus. *Space Sci. Rev.*, **20**, 357-387, doi:10.1007/BF02186459.

Kawata, Y., and J.E. Hansen, 1976: Circular polarization of sunlight reflected by Jupiter. In *Jupiter: Studies of the Interior, Atmosphere, Magneteosphere, and Satellites*. T. Gehrels, Ed. University of Arizona Press, pp. 516-530.

Somerville, R.C.J., W.J. Quirk, J.E. Hansen, A.A. Lacis, and P.H. Stone, 1976: A search for short-term meteorological effects of solar variability in an atmospheric circulation model. *J. Geophys. Res.*, **81**, 1572-1576.

Wang, W.-C., Y.L. Yung, A.A. Lacis, T. Mo, and J.E. Hansen, 1976: Greenhouse effects due to man-made perturbation of trace gases. *Science*, **194**, 685-690, doi:10.1126/science.194.4266.685

Hansen, J.E. (Ed.), 1975: *The Atmosphere of Venus*. NASA SP-382. National Aeronautics and Space Administration.

Kawabata, K., and J.E. Hansen, 1975: Interpretation of the variation of polarization over the disk of Venus. *J. Atmos. Sci.*, **32**, 1133-1139, doi:10.1175/1520-0469(1975)032<1133:IOTVOP>2.0.CO;2

Hansen, J.E., and J.W. Hovenier, 1974: Interpretation of the polarization of Venus. *J. Atmos. Sci.*, **31**, 1137-1160, doi:10.1175/1520-0469(1974)031<1137:IOTPOV>2.0.CO;2.

Hansen, J.E., and L.D. Travis, 1974: Light scattering in planetary atmospheres. *Space Sci. Rev.*, **16**, 527-610, doi:10.1007/BF00168069.

Lacis, A.A., and J.E. Hansen, 1974: A parameterization for the absorption of solar radiation in the Earth's atmosphere. *J. Atmos. Sci.*, **31**, 118-133, doi:10.1175/1520-0469(1974)031<0118:APFTAO>2.0.CO;2.

Lacis, A.A., and J.E. Hansen, 1974: Atmosphere of Venus: Implications of Venera 8 sunlight measurements. *Science*, **184**, 979-983, doi:10.1126/science.184.4140.979.

Somerville, R.C.J., P.H. Stone, M. Halem, J.E. Hansen, J.S. Hogan, L.M. Druyan, G. Russell, A.A. Lacis, W.J. Quirk, and J. Tenenbaum, 1974: The GISS model of the global atmosphere. *J. Atmos. Sci.*, **31**, 84-117, doi:10.1175/1520-0469(1974)031<0084:TGMOTG>2.0.CO;2.

Whitehill, L.P., and J.E. Hansen, 1973: On the interpretation of the "inverse phase effect" for CO_2 equivalent widths on Venus. *Icarus*, **20**, 146-152, doi:10.1016/0019-1035(73)90047-X.

Hansen, J.E., 1971: Multiple scattering of polarized light in planetary atmospheres. Part I. The doubling method. *J. Atmos. Sci.*, **28**, 120-125, doi:10.1175/1520-0469(1971)028<0120:MSOPLI>2.0.CO;2.

Hansen, J.E., 1971: Multiple scattering of polarized light in planetary atmospheres. Part II. Sunlight reflected by terrestrial water clouds. *J. Astmos. Sci.*, **28**, 1400-1426, doi:10.1175/1520 0469(1971)028<1400:MSOPLI>2.0.CO;2.

Hansen, J.E., 1971: Circular polarization of sunlight reflected by clouds. *J. Atmos. Sci.*, **28**, 1515-1516, doi:10.1175/1520-0469(1971)028<1515:CPOSRB>2.0.CO;2.

Hansen, J.E., and A. Arking, 1971: Clouds of Venus: Evidence for their nature. *Science*, **171**, 669-672, doi:10.1126/science.171.3972.669.

Hansen, J.E., and J.W. Hovenier, 1971: The doubling method applied to multiple scattering of polarized light. *J. Quant. Spectrosc. Radiat. Transfer*, **11**, 809-812, doi:10.1016/0022-4073(71)90057-4.

Liou, K.-N., and J.E Hansen, 1971: Intensity and polarization for single scattering by polydisperse spheres: A comparison of ray optics and Mie theory. *J. Atmos. Sci.*, **28**, 995-1004, doi:10.1175/1520-0469(1971)028<0995:IAPFSS>2.0.CO;2.

Hansen, J.E., and J.B. Pollack, 1970: Near-infrared light scattering by terrestrial clouds. *J. Atmos. Sci.*, **27**, 265-281, doi:10.1175/1520-0469(1970)027<0265:NILSBT>2.0.CO;2.

Hansen, J.E., 1969: Absorption-line formation in a scattering planetary atmosphere: A test of Van de Hulst's similarity relations. *Astrophys. J.*, **158**, 337-349.

Hansen, J.E., 1969: Exact and approximate solutions for multiple scattering by cloud and hazy planetary atmospheres. *J. Atmos. Sci.*, **26**, 478-487, doi:10.1175/1520-0469(1969)026<0478:EAASFM>2.0.CO;2.

Hansen, J.E., 1969: Radiative transfer by doubling very thin layers. *Astrophys. J.*, **155**, 565-573, doi:10.1086/149892.

Hansen, J.E., and H. Cheyney, 1969: Theoretical spectral scattering of ice clouds in the near infrared. *J. Geophys. Res.*, **74**, 3337-3346.

Hansen, J.E., and H. Cheyney, 1968: Near infrared reflectivity of Venus and ice clouds. *J. Atmos. Sci.*, **25**, 629-633, doi:10.1175/1520-0469(1968)025<0629:NIROVA>2.0.CO;2.

Hansen, J.E., and H. Cheyney, 1968: Comments on the paper by D.G. Rea and B.T. O'Leary, "On the composition of the Venus clouds". *J. Geophys. Res.*, **73**, 6136-6137, doi:10.1029/JB073i018p06136.

Hansen, J.E., and S. Matsushima, 1967: The atmosphere and surface temperature of Venus: A dust insulation model. *Astrophys. J.*, **150**, 1139-1157.

Hansen, J.E., and S. Matsushima, 1966: Light illuminance and color in the Earth's shadow. *J. Geophys. Rev.*, **71**, 1073-1081, doi:10.1029/JZ071i004p01073.

Matsushima, S., J.R. Zink, and J.E. Hansen, 1966: Atmospheric extinction by dust particles as determined from three-color photometry of the lunar eclipse of 19 December 1964. *Astron. J.*, **71**, 103-110.

OPEN ACCESS Freely available online

PLOS | ONE

Review

Assessing ''Dangerous Climate Change'': Required Reduction of Carbon Emissions to Protect Young People, Future Generations and Nature

James Hansen[1]*, Pushker Kharecha[1,2], Makiko Sato[1], Valerie Masson-Delmotte[3], Frank Ackerman[4], David J. Beerling[5], Paul J. Hearty[6], Ove Hoegh-Guldberg[7], Shi-Ling Hsu[8], Camille Parmesan[9,10], Johan Rockstrom[11], Eelco J. Rohling[12,13], Jeffrey Sachs[1], Pete Smith[14], Konrad Steffen[15], Lise Van Susteren[16], Karina von Schuckmann[17], James C. Zachos[18]

1 Earth Institute, Columbia University, New York, New York, United States of America, **2** Goddard Institute for Space Studies, NASA, New York, New York, United States of America, **3** Institut Pierre Simon Laplace, Laboratoire des Sciences du Climat et de l'Environnement (CEA-CNRS-UVSQ), Gif-sur-Yvette, France, **4** Synapse Energy Economics, Cambridge, Massachusetts, United States of America, **5** Department of Animal and Plant Sciences, University of Sheffield, Sheffield, South Yorkshire, United Kingdom, **6** Department of Environmental Studies, University of North Carolina, Wilmington, North Carolina, United States of America, **7** Global Change Institute, University of Queensland, St. Lucia, Queensland, Australia, **8** College of Law, Florida State University, Tallahassee, Florida, United States of America, **9** Marine Institute, Plymouth University, Plymouth, Devon, United Kingdom, **10** Integrative Biology, University of Texas, Austin, Texas, United States of America, **11** Stockholm Resilience Center, Stockholm University, Stockholm, Sweden, **12** School of Ocean and Earth Science, University of Southampton, Southampton, Hampshire, United Kingdom, **13** Research School of Earth Sciences, Australian National University, Canberra, ACT, Australia, **14** University of Aberdeen, Aberdeen, Scotland, United Kingdom, **15** Swiss Federal Institute of Technology, Swiss Federal Research Institute WSL, Zurich, Switzerland, **16** Center for Health and the Global Environment, Advisory Board, Harvard School of Public Health, Boston, Massachusetts, United States of America, **17** L'Institut Francais de Recherche pour l'Exploitation de la Mer, Ifremer, Toulon, France, **18** Earth and Planetary Science, University of California, Santa Cruz, CA, United States of America

Abstract: We assess climate impacts of global warming using ongoing observations and paleoclimate data. We use Earth's measured energy imbalance, paleoclimate data, and simple representations of the global carbon cycle and temperature to define emission reductions needed to stabilize climate and avoid potentially disastrous impacts on today's young people, future generations, and nature. A cumulative industrial-era limit of ~500 GtC fossil fuel emissions and 100 GtC storage in the biosphere and soil would keep climate close to the Holocene range to which humanity and other species are adapted. Cumulative emissions of ~1000 GtC, sometimes associated with 2°C global warming, would spur ''slow'' feedbacks and eventual warming of 3–4°C with disastrous consequences. Rapid emissions reduction is required to restore Earth's energy balance and avoid ocean heat uptake that would practically guarantee irreversible effects. Continuation of high fossil fuel emissions, given current knowledge of the consequences, would be an act of extraordinary witting intergenerational injustice. Responsible policymaking requires a rising price on carbon emissions that would preclude emissions from most remaining coal and unconventional fossil fuels and phase down emissions from conventional fossil fuels.

Introduction

Humans are now the main cause of changes of Earth's atmospheric composition and thus the drive for future climate change [1]. The principal climate forcing, defined as an imposed change of planetary energy balance [1–2], is increasing carbon dioxide (CO_2) from fossil fuel emissions, much of which will remain in the atmosphere for millennia [1,3]. The climate response to this forcing and society's response to climate change are complicated by the system's inertia, mainly due to the ocean and the ice sheets on Greenland and Antarctica together with the long residence time of fossil fuel carbon in the climate system. The inertia causes climate to appear to respond slowly to this human-made forcing, but further long-lasting responses can be locked in.

More than 170 nations have agreed on the need to limit fossil fuel emissions to avoid dangerous human-made climate change, as formalized in the 1992 Framework Convention on Climate Change [6]. However, the stark reality is that global emissions have accelerated (Fig. 1) and new efforts are underway to massively expand fossil fuel extraction [7–9] by drilling to increasing ocean depths and into the Arctic, squeezing oil from tar sands and tar shale, hydro-fracking to expand extraction of natural gas, developing exploitation of methane hydrates, and mining of coal via mountaintop removal and mechanized longwall mining. The growth rate of fossil fuel emissions increased from 1.5%/year during 1980–2000 to 3%/year in 2000–2012, mainly because of increased coal use [4–5].

The Framework Convention [6] does not define a dangerous level for global warming or an emissions limit for fossil fuels. The

Citation: Hansen J, Kharecha P, Sato M, Masson-Delmotte V, Ackerman F, et al. (2013) Assessing ''Dangerous Climate Change'': Required Reduction of Carbon Emissions to Protect Young People, Future Generations and Nature. PLoS ONE 8(12): e81648. doi:10.1371/journal.pone.0081648

Editor: Juan A. Añel, University of Oxford, United Kingdom

Published December 3, 2013

Funding: Funding came from: NASA Climate Research Funding, Gifts to Columbia University from H.F. (''Gerry'') Lenfest, private philanthropist (no web site, but see http://en.wikipedia.org/wiki/H._F._Lenfest), Jim Miller, Lee Wasserman (Rockefeller Family Fund) (http://www.rffund.org/), Flora Family Foundation (http://www.florafamily.org/), Jeremy Grantham, ClimateWorks and the Energy Foundation provided support for Hansen's Climate Science, Awareness and Solutions program at Columbia University to complete this research and publication. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing Interests: The authors have declared that no competing interests exist.

* E-mail: jimehansen@gmail.com

Exhibit 2 to Declaration of Dr. James E. Hansen

Exhibit A 42

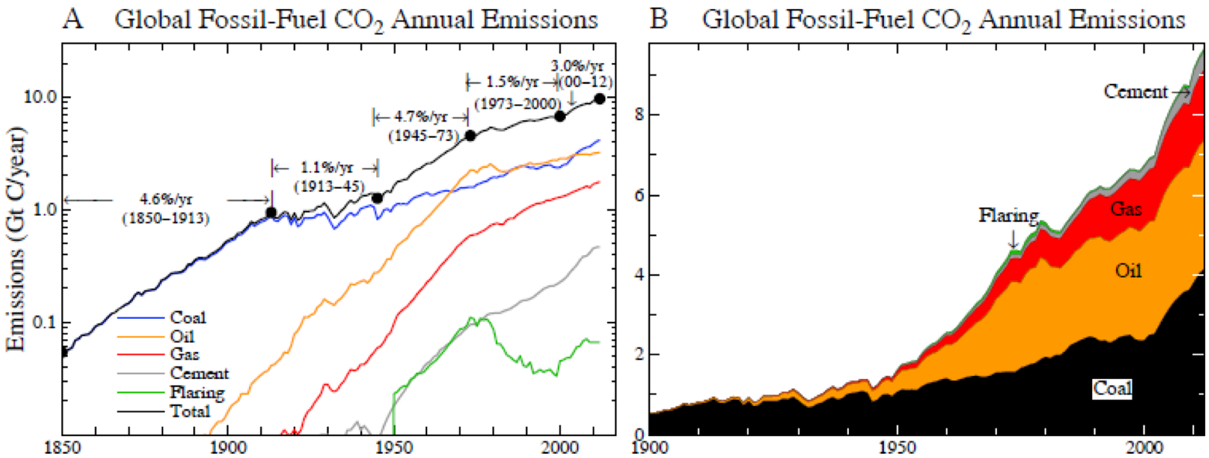


Figure 1. CO_2 annual emissions from fossil fuel use and cement manufacture, based on data of British Petroleum [4] concatenated with data of Boden et al. [5]. (A) is log scale and (B) is linear.
doi:10.1371/journal.pone.0081648.g001

European Union in 1996 proposed to limit global warming to 2°C relative to pre-industrial times [10], based partly on evidence that many ecosystems are at risk with larger climate change. The 2°C target was reaffirmed in the 2009 "Copenhagen Accord" emerging from the 15th Conference of the Parties of the Framework Convention [11], with specific language "We agree that deep cuts in global emissions are required according to science, as documented in the IPCC Fourth Assessment Report with a view to reduce global emissions so as to hold the increase in global temperature below 2 degrees Celsius…".

A global warming target is converted to a fossil fuel emissions target with the help of global climate-carbon-cycle models, which reveal that eventual warming depends on cumulative carbon emissions, not on the temporal history of emissions [12]. The emission limit depends on climate sensitivity, but central estimates [12–13], including those in the upcoming Fifth Assessment of the Intergovernmental Panel on Climate Change [14], are that a 2°C global warming limit implies a cumulative carbon emissions limit of the order of 1000 GtC. In comparing carbon emissions, note that some authors emphasize the sum of fossil fuel and deforestation carbon. We bookkeep fossil fuel and deforestation carbon separately, because the larger fossil fuel term is known more accurately and this carbon stays in the climate system for hundreds of thousands of years. Thus fossil fuel carbon is the crucial human input that must be limited. Deforestation carbon is more uncertain and potentially can be offset on the century time scale by storage in the biosphere, including the soil, via reforestation and improved agricultural and forestry practices.

There are sufficient fossil fuel resources to readily supply 1000 GtC, as fossil fuel emissions to date (370 GtC) are only a small fraction of potential emissions from known reserves and potentially recoverable resources (Fig. 2). Although there are uncertainties in reserves and resources, ongoing fossil fuel subsidies and continuing technological advances ensure that more and more of these fuels will be economically recoverable. As we will show, Earth's paleoclimate record makes it clear that the CO_2 produced by burning all or most of these fossil fuels would lead to a very different planet than the one that humanity knows.

Our evaluation of a fossil fuel emissions limit is not based on climate models but rather on observational evidence of global climate change as a function of global temperature and on the fact that climate stabilization requires long-term planetary energy balance. We use measured global temperature and Earth's measured energy imbalance to determine the atmospheric CO_2 level required to stabilize climate at today's global temperature, which is near the upper end of the global temperature range in the current interglacial period (the Holocene). We then examine climate impacts during the past few decades of global warming and in paleoclimate records including the Eemian period, concluding that there are already clear indications of undesirable impacts at the current level of warming and that 2°C warming would have major deleterious consequences. We use simple representations of the carbon cycle and global temperature, consistent with observations, to simulate transient global temperature and assess carbon emission scenarios that could keep global climate near the Holocene range. Finally, we discuss likely overshooting of target emissions, the potential for carbon extraction from the atmosphere, and implications for energy and economic policies, as well as intergenerational justice.

Global Temperature and Earth's Energy Balance

Global temperature and Earth's energy imbalance provide our most useful measuring sticks for quantifying global climate change and the changes of global climate forcings that would be required to stabilize global climate. Thus we must first quantify knowledge of these quantities.

Temperature

Temperature change in the past century (Fig. 3; update of figures in [16]) includes unforced variability and forced climate change. The long-term global warming trend is predominantly a forced climate change caused by increased human-made atmospheric gases, mainly CO_2 [1]. Increase of "greenhouse" gases such as CO_2 has little effect on incoming sunlight but makes the atmosphere more opaque at infrared wavelengths, causing infrared (heat) radiation to space to emerge from higher, colder levels, which thus reduces infrared radiation to space. The resulting planetary energy imbalance, absorbed solar energy exceeding heat emitted to space, causes Earth to warm. Observations, discussed below, confirm that Earth is now substantially out of energy balance, so the long-term warming will continue.

Exhibit 2 to Declaration of Dr. James E. Hansen
Exhibit A 43

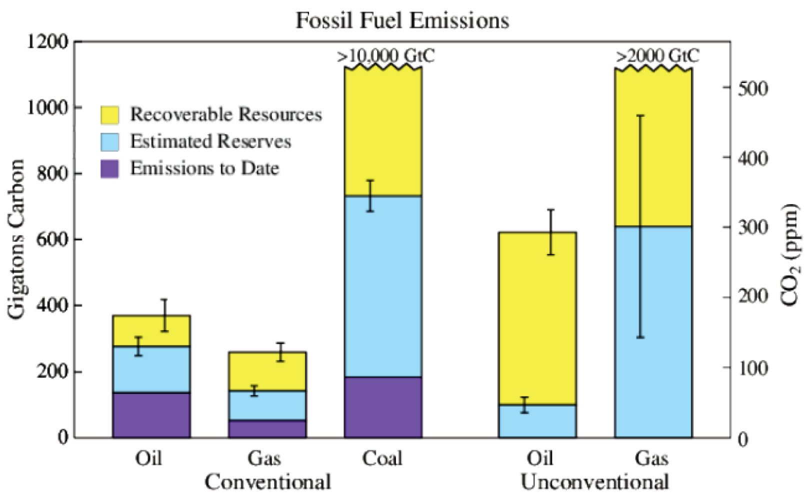


Figure 2. Fossil fuel CO_2 emissions and carbon content (1 ppm atmospheric CO_2 ~ 2.12 GtC). Estimates of reserves (profitable to extract at current prices) and resources (potentially recoverable with advanced technology and/or at higher prices) are the mean of estimates of Energy Information Administration (EIA) [7], German Advisory Council (GAC) [8], and Global Energy Assessment (GEA) [9]. GEA [9] suggests the possibility of >15,000 GtC unconventional gas. Error estimates (vertical lines) are from GEA and probably underestimate the total uncertainty. We convert energy content to carbon content using emission factors of Table 4.2 of [15] for coal, gas and conventional oil, and, also following [15], emission factor of unconventional oil is approximated as being the same as for coal. Total emissions through 2012, including gas flaring and cement manufacture, are 384 GtC; fossil fuel emissions alone are ~370 GtC.
doi:10.1371/journal.pone.0081648.g002

Global temperature appears to have leveled off since 1998 (Fig. 3a). That plateau is partly an illusion due to the 1998 global temperature spike caused by the El Niño of the century that year. The 11-year (132-month) running mean temperature (Fig. 3b) shows only a moderate decline of the warming rate. The 11-year averaging period minimizes the effect of variability due to the 10–12 year periodicity of solar irradiance as well as irregular El Niño/La Niña warming/cooling in the tropical Pacific Ocean. The current solar cycle has weaker irradiance than the several prior solar cycles, but the decreased irradiance can only partially account for the decreased warming rate [17]. Variability of the El Niño/La Niña cycle, described as a Pacific Decadal Oscillation, largely accounts for the temporary decrease of warming [18], as we discuss further below in conjunction with global temperature simulations.

Assessments of dangerous climate change have focused on estimating a permissible level of global warming. The Intergovernmental Panel on Climate Change [1,19] summarized broad-based assessments with a "burning embers" diagram, which indicated that major problems begin with global warming of 2–3°C. A probabilistic analysis [20], still partly subjective, found a median "dangerous" threshold of 2.8°C, with 95% confidence that the dangerous threshold was 1.5°C or higher. These assessments were relative to global temperature in year 1990, so add 0.6°C to these values to obtain the warming relative to 1880–1920, which is the base period we use in this paper for preindustrial time. The conclusion that humanity could tolerate global warming up to a few degrees Celsius meshed with common sense. After all, people readily tolerate much larger regional and seasonal climate variations.

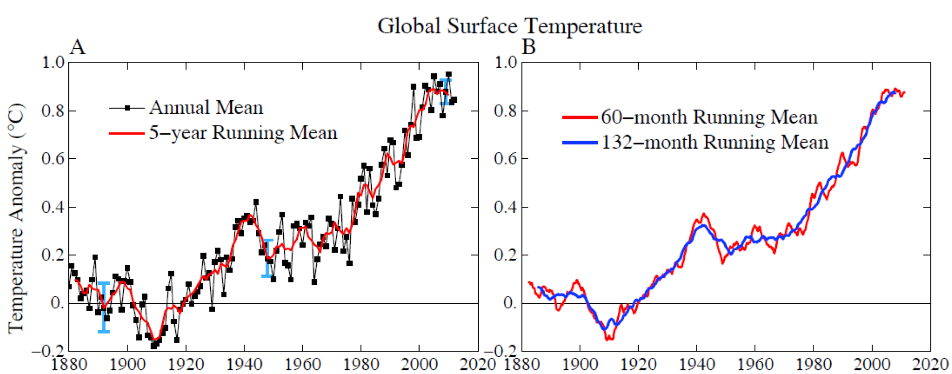


Figure 3. Global surface temperature relative to 1880–1920 mean. B shows the 5 and 11 year means. Figures are updates of [16] using data through August 2013.
doi:10.1371/journal.pone.0081648.g003

The fallacy of this logic emerged recently as numerous impacts of ongoing global warming emerged and as paleoclimate implications for climate sensitivity became apparent. Arctic sea ice end-of-summer minimum area, although variable from year to year, has plummeted by more than a third in the past few decades, at a faster rate than in most models [21], with the sea ice thickness declining a factor of four faster than simulated in IPCC climate models [22]. The Greenland and Antarctic ice sheets began to shed ice at a rate, now several hundred cubic kilometers per year, which is continuing to accelerate [23–25]. Mountain glaciers are receding rapidly all around the world [26–29] with effects on seasonal freshwater availability of major rivers [30–32]. The hot dry subtropical climate belts have expanded as the troposphere has warmed and the stratosphere cooled [33–36], contributing to increases in the area and intensity of drought [37] and wildfires [38]. The abundance of reef-building corals is decreasing at a rate of 0.5–2%/year, at least in part due to ocean warming and possibly ocean acidification caused by rising dissolved CO_2 [39–41]. More than half of all wild species have shown significant changes in where they live and in the timing of major life events [42–44]. Mega-heatwaves, such as those in Europe in 2003, the Moscow area in 2010, Texas and Oklahoma in 2011, Greenland in 2012, and Australia in 2013 have become more widespread with the increase demonstrably linked to global warming [45–47].

These growing climate impacts, many more rapid than anticipated and occurring while global warming is less than 1°C, imply that society should reassess what constitutes a "dangerous level" of global warming. Earth's paleoclimate history provides a valuable tool for that purpose.

Paleoclimate Temperature

Major progress in quantitative understanding of climate change has occurred recently by use of the combination of data from high resolution ice cores covering time scales of order several hundred thousand years [48–49] and ocean cores for time scales of order one hundred million years [50]. Quantitative insights on global temperature sensitivity to external forcings [51–52] and sea level sensitivity to global temperature [52–53] are crucial to our analyses. Paleoclimate data also provide quantitative information about how nominally slow feedback processes amplify climate sensitivity [51–52,54–56], which also is important to our analyses.

Earth's surface temperature prior to instrumental measurements is estimated via proxy data. We will refer to the surface temperature record in Fig. 4 of a recent paper [52]. Global mean temperature during the Eemian interglacial period (120,000 years ago) is constrained to be 2°C warmer than our pre-industrial (1880–1920) level based on several studies of Eemian climate [52]. The concatenation of modern and instrumental records [52] is based on an estimate that global temperature in the first decade of the 21st century (+0.8°C relative to 1880–1920) exceeded the Holocene mean by 0.25 ± 0.25°C. That estimate was based in part on the fact that sea level is now rising 3.2 mm/yr (3.2 m/millennium) [57], an order of magnitude faster than the rate during the prior several thousand years, with rapid change of ice sheet mass balance over the past few decades [23] and Greenland and Antarctica now losing mass at accelerating rates [23–24]. This concatenation, which has global temperature 13.9°C in the base period 1951–1980, has the first decade of the 21st century slightly (~0.1°C) warmer than the early Holocene maximum. A recent reconstruction from proxy temperature data [55] concluded that global temperature declined about 0.7°C between the Holocene maximum and a pre-industrial minimum before recent warming brought temperature back near the Holocene maximum, which is consistent with our analysis.

Climate oscillations evident in Fig. 4 of Hansen et al. [52] were instigated by perturbations of Earth's orbit and spin axis tilt relative to the orbital plane, which alter the geographical and seasonal distribution of sunlight on Earth [58]. These forcings change slowly, with periods between 20,000 and 400,000 years, and thus climate is able to stay in quasi-equilibrium with these forcings. Slow insolation changes initiated the climate oscillations, but the mechanisms that caused the climate changes to be so large were two powerful amplifying feedbacks: the planet's surface albedo (its reflectivity, literally its whiteness) and atmospheric CO_2 amount. As the planet warms, ice and snow melt, causing the surface to be darker, absorb more sunlight and warm further. As the ocean and soil become warmer they release CO_2 and other greenhouse gases, causing further warming. Together with fast feedbacks processes, via changes of water vapor, clouds, and the vertical temperature profile, these slow amplifying feedbacks were responsible for almost the entire glacial-to-interglacial temperature change [59–62].

The albedo and CO_2 feedbacks amplified weak orbital forcings, the feedbacks necessarily changing slowly over millennia, at the pace of orbital changes. Today, however, CO_2 is under the control of humans as fossil fuel emissions overwhelm natural changes. Atmospheric CO_2 has increased rapidly to a level not seen for at least 3 million years [56,63]. Global warming induced by increasing CO_2 will cause ice to melt and hence sea level to rise as the global volume of ice moves toward the quasi-equilibrium amount that exists for a given global temperature [53]. As ice melts and ice area decreases, the albedo feedback will amplify global warming.

Earth, because of the climate system's inertia, has not yet fully responded to human-made changes of atmospheric composition. The ocean's thermal inertia, which delays some global warming for decades and even centuries, is accounted for in global climate models and its effect is confirmed via measurements of Earth's energy balance (see next section). In addition there are slow climate feedbacks, such as changes of ice sheet size, that occur mainly over centuries and millennia. Slow feedbacks have little effect on the immediate planetary energy balance, instead coming into play in response to temperature change. The slow feedbacks are difficult to model, but paleoclimate data and observations of ongoing changes help provide quantification.

Earth's Energy Imbalance

At a time of climate stability, Earth radiates as much energy to space as it absorbs from sunlight. Today Earth is out of balance because increasing atmospheric gases such as CO_2 reduce Earth's heat radiation to space, thus causing an energy imbalance, as there is less energy going out than coming in. This imbalance causes Earth to warm and move back toward energy balance. The warming and restoration of energy balance take time, however, because of Earth's thermal inertia, which is due mainly to the global ocean.

Earth warmed about 0.8°C in the past century. That warming increased Earth's radiation to space, thus reducing Earth's energy imbalance. The remaining energy imbalance helps us assess how much additional warming is still "in the pipeline". Of course increasing CO_2 is only one of the factors affecting Earth's energy balance, even though it is the largest climate forcing. Other forcings include changes of aerosols, solar irradiance, and Earth's surface albedo.

Determination of the state of Earth's climate therefore requires measuring the energy imbalance. This is a challenge, because the imbalance is expected to be only about 1 W/m^2 or less, so accuracy approaching 0.1 W/m^2 is needed. The most promising

Exhibit 2 to Declaration of Dr. James E. Hansen

Exhibit A 45

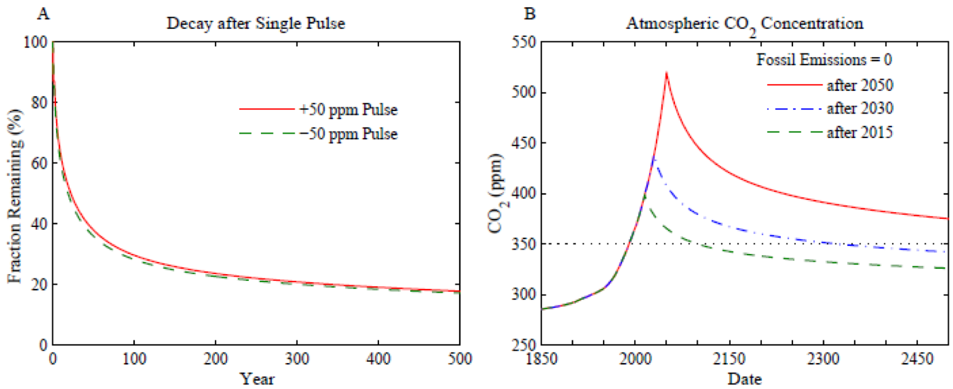


Figure 4. Decay of atmospheric CO_2 perturbations. (A) Instantaneous injection or extraction of CO_2 with initial conditions at equilibrium. (B) Fossil fuel emissions terminate at the end of 2015, 2030, or 2050 and land use emissions terminate after 2015 in all three cases, i.e., thereafter there is no net deforestation.
doi:10.1371/journal.pone.0081648.g004

approach is to measure the rate of changing heat content of the ocean, atmosphere, land, and ice [64]. Measurement of ocean heat content is the most critical observation, as nearly 90 percent of the energy surplus is stored in the ocean [64–65].

Observed Energy Imbalance

Nations of the world have launched a cooperative program to measure changing ocean heat content, distributing more than 3000 Argo floats around the world ocean, with each float repeatedly diving to a depth of 2 km and back [66]. Ocean coverage by floats reached 90% by 2005 [66], with the gaps mainly in sea ice regions, yielding the potential for an accurate energy balance assessment, provided that several systematic measurement biases exposed in the past decade are minimized [67–69].

Argo data reveal that in 2005–2010 the ocean's upper 2000 m gained heat at a rate equal to 0.41 W/m^2 averaged over Earth's surface [70]. Smaller contributions to planetary energy imbalance are from heat gain by the deeper ocean (+0.10 W/m^2), energy used in net melting of ice (+0.05 W/m^2), and energy taken up by warming continents (+0.02 W/m^2). Data sources for these estimates and uncertainties are provided elsewhere [64]. The resulting net planetary energy imbalance for the six years 2005–2010 is $+0.58\pm0.15$ W/m^2.

The positive energy imbalance in 2005–2010 confirms that the effect of solar variability on climate is much less than the effect of human-made greenhouse gases. If the sun were the dominant forcing, the planet would have a negative energy balance in 2005–2010, when solar irradiance was at its lowest level in the period of accurate data, i.e., since the 1970s [64,71]. Even though much of the greenhouse gas forcing has been expended in causing observed 0.8°C global warming, the residual positive forcing overwhelms the negative solar forcing. The full amplitude of solar cycle forcing is about 0.25 W/m^2 [64,71], but the reduction of solar forcing due to the present weak solar cycle is about half that magnitude as we illustrate below, so the energy imbalance measured during solar minimum (0.58 W/m^2) suggests an average imbalance over the solar cycle of about 0.7 W/m^2.

Earth's measured energy imbalance has been used to infer the climate forcing by aerosols, with two independent analyses yielding a forcing in the past decade of about -1.5 W/m^2 [64,72], including the direct aerosol forcing and indirect effects via induced cloud changes. Given this large (negative) aerosol forcing, precise monitoring of changing aerosols is needed [73]. Public reaction to increasingly bad air quality in developing regions [74] may lead to future aerosol reductions, at least on a regional basis. Increase of Earth's energy imbalance from reduction of particulate air pollution, which is needed for the sake of human health, can be minimized via an emphasis on reducing absorbing black soot [75], but the potential to constrain the net increase of climate forcing by focusing on black soot is limited [76].

Energy Imbalance Implications for CO_2 Target

Earth's energy imbalance is the most vital number characterizing the state of Earth's climate. It informs us about the global temperature change "in the pipeline" without further change of climate forcings and it defines how much greenhouse gases must be reduced to restore Earth's energy balance, which, at least to a good approximation, must be the requirement for stabilizing global climate. The measured energy imbalance accounts for all natural and human-made climate forcings, including changes of atmospheric aerosols and Earth's surface albedo.

If Earth's mean energy imbalance today is +0.5 W/m^2, CO_2 must be reduced from the current level of 395 ppm (global-mean annual-mean in mid-2013) to about 360 ppm to increase Earth's heat radiation to space by 0.5 W/m^2 and restore energy balance. If Earth's energy imbalance is 0.75 W/m^2, CO_2 must be reduced to about 345 ppm to restore energy balance [64,75].

The measured energy imbalance indicates that an initial CO_2 target "$<$350 ppm" would be appropriate, if the aim is to stabilize climate without further global warming. That target is consistent with an earlier analysis [54]. Additional support for that target is provided by our analyses of ongoing climate change and paleoclimate, in later parts of our paper. Specification now of a CO_2 target more precise than $<$350 ppm is difficult and unnecessary, because of uncertain future changes of forcings including other gases, aerosols and surface albedo. More precise assessments will become available during the time that it takes to turn around CO_2 growth and approach the initial 350 ppm target.

Below we find the decreasing emissions scenario that would achieve the 350 ppm target within the present century. Specifically, we want to know the annual percentage rate at which emissions must be reduced to reach this target, and the dependence of this rate upon the date at which reductions are initiated. This approach is complementary to the approach of estimating cumulative emissions allowed to achieve a given limit on global warming [12].

Exhibit 2 to Declaration of Dr. James E. Hansen
Exhibit A 46

If the only human-made climate forcing were changes of atmospheric CO_2, the appropriate CO_2 target might be close to the pre-industrial CO_2 amount [53]. However, there are other human forcings, including aerosols, the effect of aerosols on clouds, non-CO_2 greenhouse gases, and changes of surface albedo that will not disappear even if fossil fuel burning is phased out. Aerosol forcings are substantially a result of fossil fuel burning [1,76], but the net aerosol forcing is a sensitive function of various aerosol sources [76]. The indirect aerosol effect on clouds is non-linear [1,76] such that it has been suggested that even the modest aerosol amounts added by pre-industrial humans to an otherwise pristine atmosphere may have caused a significant climate forcing [59]. Thus continued precise monitoring of Earth's radiation imbalance is probably the best way to assess and adjust the appropriate CO_2 target.

Ironically, future reductions of particulate air pollution may exacerbate global warming by reducing the cooling effect of reflective aerosols. However, a concerted effort to reduce non-CO_2 forcings by methane, tropospheric ozone, other trace gases, and black soot might counteract the warming from a decline in reflective aerosols [54,75]. Our calculations below of future global temperature assume such compensation, as a first approximation. To the extent that goal is not achieved, adjustments must be made in the CO_2 target or future warming may exceed calculated values.

Climate Impacts

Determination of the dangerous level of global warming inherently is partly subjective, but we must be as quantitative as possible. Early estimates for dangerous global warming based on the "burning embers" approach [1,19–20] have been recognized as probably being too conservative [77]. A target of limiting warming to 2°C has been widely adopted, as discussed above. We suspect, however, that this may be a case of inching toward a better answer. If our suspicion is correct, then that gradual approach is itself very dangerous, because of the climate system's inertia. It will become exceedingly difficult to keep warming below a target smaller than 2°C, if high emissions continue much longer.

We consider several important climate impacts and use evidence from current observations to assess the effect of 0.8°C warming and paleoclimate data for the effect of larger warming, especially the Eemian period, which had global mean temperature about +2°C relative to pre-industrial time. Impacts of special interest are sea level rise and species extermination, because they are practically irreversible, and others important to humankind.

Sea Level

The prior interglacial period, the Eemian, was at most ~2°C warmer than 1880–1920 (Fig. 3). Sea level reached heights several meters above today's level [78–80], probably with instances of sea level change of the order of 1 m/century [81–83]. Geologic shoreline evidence has been interpreted as indicating a rapid sea level rise of a few meters late in the Eemian to a peak about 9 meters above present, suggesting the possibility that a critical stability threshold was crossed that caused polar ice sheet collapse [84–85], although there remains debate within the research community about this specific history and interpretation. The large Eemian sea level excursions imply that substantial ice sheet melting occurred when the world was little warmer than today.

During the early Pliocene, which was only ~3°C warmer than the Holocene, sea level attained heights as much as 15–25 meters higher than today [53,86–89]. Such sea level rise suggests that parts of East Antarctica must be vulnerable to eventual melting with global temperature increase of a few degrees Celsius. Indeed, satellite gravity data and radar altimetry reveal that the Totten Glacier of East Antarctica, which fronts a large ice mass grounded below sea level, is now losing mass [90].

Greenland ice core data suggest that the Greenland ice sheet response to Eemian warmth was limited [91], but the fifth IPCC assessment [14] concludes that Greenland very likely contributed between 1.4 and 4.3 m to the higher sea level of the Eemian. The West Antarctic ice sheet is probably more susceptible to rapid change, because much of it rests on bedrock well below sea level [92–93]. Thus the entire 3–4 meters of global sea level contained in that ice sheet may be vulnerable to rapid disintegration, although arguments for stability of even this marine ice sheet have been made [94]. However, Earth's history reveals sea level changes of as much as a few meters per century, even though the natural climate forcings changed much more slowly than the present human-made forcing.

Expected human-caused sea level rise is controversial in part because predictions focus on sea level at a specific time, 2100. Sea level on a given date is inherently difficult to predict, as it depends on how rapidly non-linear ice sheet disintegration begins. Focus on a single date also encourages people to take the estimated result as an indication of what humanity faces, thus failing to emphasize that the likely rate of sea level rise immediately after 2100 will be much larger than within the 21st century, especially if CO_2 emissions continue to increase.

Recent estimates of sea level rise by 2100 have been of the order of 1 m [95–96], which is higher than earlier assessments [26], but these estimates still in part assume linear relations between warming and sea level rise. It has been argued [97–98] that continued business-as-usual CO_2 emissions are likely to spur a nonlinear response with multi-meter sea level rise this century. Greenland and Antarctica have been losing mass at rapidly increasing rates during the period of accurate satellite data [23]; the data are suggestive of exponential increase, but the records are too short to be conclusive. The area on Greenland with summer melt has increased markedly, with 97% of Greenland experiencing melt in 2012 [99].

The important point is that the uncertainty is not about whether continued rapid CO_2 emissions would cause large sea level rise, submerging global coastlines – it is about how soon the large changes would begin. The carbon from fossil fuel burning will remain in and affect the climate system for many millennia, ensuring that over time sea level rise of many meters will occur – tens of meters if most of the fossil fuels are burned [53]. That order of sea level rise would result in the loss of hundreds of historical coastal cities worldwide with incalculable economic consequences, create hundreds of millions of global warming refugees from highly-populated low-lying areas, and thus likely cause major international conflicts.

Shifting Climate Zones

Theory and climate models indicate that the tropical overturning (Hadley) atmospheric circulation expands poleward with global warming [33]. There is evidence in satellite and radiosonde data and in observational data for poleward expansion of the tropical circulation by as much as a few degrees of latitude since the 1970s [34–35], but natural variability may have contributed to that expansion [36]. Change in the overturning circulation likely contributes to expansion of subtropical conditions and increased aridity in the southern United States [30,100], the Mediterranean region, South America, southern Africa, Madagascar, and southern Australia. Increased aridity and temperature contribute to increased forest fires that burn hotter and are more destructive [38].

Exhibit 2 to Declaration of Dr. James E. Hansen
Exhibit A 47

Despite large year-to-year variability of temperature, decadal averages reveal isotherms (lines of a given average temperature) moving poleward at a typical rate of the order of 100 km/decade in the past three decades [101], although the range shifts for specific species follow more complex patterns [102]. This rapid shifting of climate zones far exceeds natural rates of change. Movement has been in the same direction (poleward, and upward in elevation) since about 1975. Wild species have responded to climate change, with three-quarters of marine species shifting their ranges poleward as much as 1000 km [44,103] and more than half of terrestrial species shifting ranges poleward as much as 600 km and upward as much as 400 m [104].

Humans may adapt to shifting climate zones better than many species. However, political borders can interfere with human migration, and indigenous ways of life already have been adversely affected [26]. Impacts are apparent in the Arctic, with melting tundra, reduced sea ice, and increased shoreline erosion. Effects of shifting climate zones also may be important for indigenous Americans who possess specific designated land areas, as well as other cultures with long-standing traditions in South America, Africa, Asia and Australia.

Human Extermination of Species

Biodiversity is affected by many agents including overharvesting, introduction of exotic species, land use changes, nitrogen fertilization, and direct effects of increased atmospheric CO_2 on plant ecophysiology [43]. However, an overriding role of climate change is exposed by diverse effects of rapid warming on animals, plants, and insects in the past three decades.

A sudden widespread decline of frogs, with extinction of entire mountain-restricted species attributed to global warming [105–106], provided a dramatic awakening. There are multiple causes of the detailed processes involved in global amphibian declines and extinctions [107–108], but global warming is a key contributor and portends a planetary-scale mass extinction in the making unless action is taken to stabilize climate while also fighting biodiversity's other threats [109].

Mountain-restricted and polar-restricted species are particularly vulnerable. As isotherms move up the mountainside and poleward, so does the climate zone in which a given species can survive. If global warming continues unabated, many of these species will be effectively pushed off the planet. There are already reductions in the population and health of Arctic species in the southern parts of the Arctic, Antarctic species in the northern parts of the Antarctic, and alpine species worldwide [43].

A critical factor for survival of some Arctic species is retention of all-year sea ice. Continued growth of fossil fuel emissions will cause loss of all Arctic summer sea ice within several decades. In contrast, the scenario in Fig. 5A, with global warming peaking just over 1°C and then declining slowly, should allow summer sea ice to survive and then gradually increase to levels representative of recent decades.

The threat to species survival is not limited to mountain and polar species. Plant and animal distributions reflect the regional climates to which they are adapted. Although species attempt to migrate in response to climate change, their paths may be blocked by human-constructed obstacles or natural barriers such as coast lines and mountain ranges. As the shift of climate zones [110] becomes comparable to the range of some species, less mobile species can be driven to extinction. Because of extensive species interdependencies, this can lead to mass extinctions.

Rising sea level poses a threat to a large number of uniquely evolved endemic fauna living on islands in marine-dominated ecosystems, with those living on low lying islands being especially vulnerable. Evolutionary history on Bermuda offers numerous examples of the direct and indirect impact of changing sea level on evolutionary processes [111–112], with a number of taxa being extirpated due to habitat changes, greater competition, and island inundation [113]. Similarly, on Aldahabra Island in the Indian Ocean, land tortoises were exterminated during sea level high stands [114]. Vulnerabilities would be magnified by the speed of human-made climate change and the potentially large sea level rise [115].

IPCC [26] reviewed studies relevant to estimating eventual extinctions. They estimate that if global warming exceeds 1.6°C above preindustrial, 9–31 percent of species will be committed to extinction. With global warming of 2.9°C, an estimated 21–52 percent of species will be committed to extinction. A comprehensive study of biodiversity indicators over the past decade [116] reveals that, despite some local success in increasing extent of protected areas, overall indicators of pressures on biodiversity including that due to climate change are continuing to increase and indicators of the state of biodiversity are continuing to decline.

Mass extinctions occurred several times in Earth's history [117–118], often in conjunction with rapid climate change. New species evolved over millions of years, but those time scales are almost beyond human comprehension. If we drive many species to extinction we will leave a more desolate, monotonous planet for our children, grandchildren, and more generations than we can imagine. We will also undermine ecosystem functions (e.g., pollination which is critical for food production) and ecosystem resilience (when losing keystone species in food chains), as well as reduce functional diversity (critical for the ability of ecosystems to respond to shocks and stress) and genetic diversity that plays an important role for development of new medicines, materials, and sources of energy.

Coral Reef Ecosystems

Coral reefs are the most biologically diverse marine ecosystem, often described as the rainforests of the ocean. Over a million species, most not yet described [119], are estimated to populate coral reef ecosystems generating crucial ecosystem services for at least 500 million people in tropical coastal areas. These ecosystems are highly vulnerable to the combined effects of ocean acidification and warming.

Acidification arises as the ocean absorbs CO_2, producing carbonic acid [120], thus making the ocean more corrosive to the calcium carbonate shells (exoskeletons) of many marine organisms. Geochemical records show that ocean pH is already outside its range of the past several million years [121–122]. Warming causes coral bleaching, as overheated coral expel symbiotic algae and become vulnerable to disease and mortality [123]. Coral bleaching and slowing of coral calcification already are causing mass mortalities, increased coral disease, and reduced reef carbonate accretion, thus disrupting coral reef ecosystem health [40,124].

Local human-made stresses add to the global warming and acidification effects, all of these driving a contraction of 1–2% per year in the abundance of reef-building corals [39]. Loss of the three-dimensional coral reef frameworks has consequences for all the species that depend on them. Loss of these frameworks also has consequences for the important roles that coral reefs play in supporting fisheries and protecting coastlines from wave stress. Consequences of lost coral reefs can be economically devastating for many nations, especially in combination with other impacts such as sea level rise and intensification of storms.

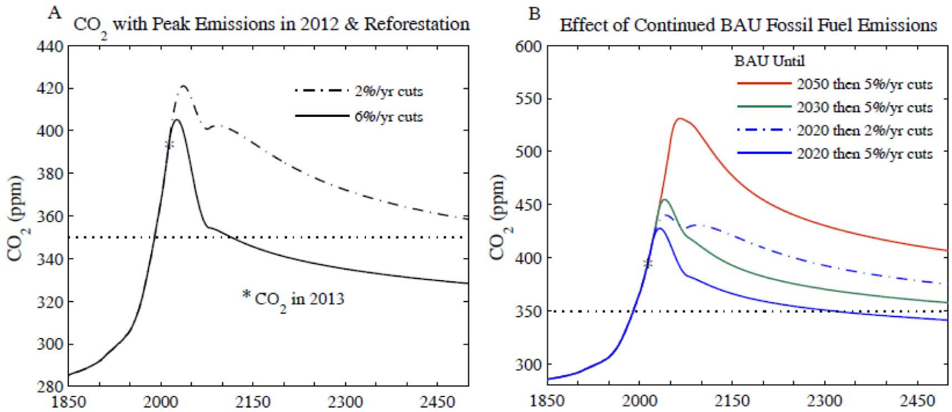


Figure 5. Atmospheric CO_2 if fossil fuel emissions reduced. (A) 6% or 2% annual cut begins in 2013 and 100 GtC reforestation drawdown occurs in 2031–2080, (B) effect of delaying onset of emission reduction.
doi:10.1371/journal.pone.0081648.g005

Climate Extremes

Changes in the frequency and magnitude of climate extremes, of both moisture and temperature, are affected by climate trends as well as changing variability. Extremes of the hydrologic cycle are expected to intensify in a warmer world. A warmer atmosphere holds more moisture, so precipitation can be heavier and cause more extreme flooding. Higher temperatures, on the other hand, increase evaporation and can intensify droughts when they occur, as can expansion of the subtropics, as discussed above. Global models for the 21st century find an increased variability of precipitation minus evaporation [P-E] in most of the world, especially near the equator and at high latitudes [125]. Some models also show an intensification of droughts in the Sahel, driven by increasing greenhouse gases [126].

Observations of ocean salinity patterns for the past 50 years reveal an intensification of [P-E] patterns as predicted by models, but at an even faster rate. Precipitation observations over land show the expected general increase of precipitation poleward of the subtropics and decrease at lower latitudes [1,26]. An increase of intense precipitation events has been found on much of the world's land area [127–129]. Evidence for widespread drought intensification is less clear and inherently difficult to confirm with available data because of the increase of time-integrated precipitation at most locations other than the subtropics. Data analyses have found an increase of drought intensity at many locations [130–131] The magnitude of change depends on the drought index employed [132], but soil moisture provides a good means to separate the effect of shifting seasonal precipitation and confirms an overall drought intensification [37].

Global warming of ~0.6°C since the 1970s (Fig. 3) has already caused a notable increase in the occurrence of extreme summer heat [46]. The likelihood of occurrence or the fractional area covered by 3-standard-deviation hot anomalies, relative to a base period (1951–1980) that was still within the range of Holocene climate, has increased by more than a factor of ten. Large areas around Moscow, the Mediterranean region, the United States and Australia have experienced such extreme anomalies in the past three years. Heat waves lasting for weeks have a devastating impact on human health: the European heat wave of summer 2003 caused over 70,000 excess deaths [133]. This heat record for Europe was surpassed already in 2010 [134]. The number of extreme heat waves has increased several-fold due to global warming [45–46,135] and will increase further if temperatures continue to rise.

Human Health

Impacts of climate change cause widespread harm to human health, with children often suffering the most. Food shortages, polluted air, contaminated or scarce supplies of water, an expanding area of vectors causing infectious diseases, and more intensely allergenic plants are among the harmful impacts [26]. More extreme weather events cause physical and psychological harm. World health experts have concluded with "very high confidence" that climate change already contributes to the global burden of disease and premature death [26].

IPCC [26] projects the following trends, if global warming continue to increase, where only trends assigned very high confidence or high confidence are included: (i) increased malnutrition and consequent disorders, including those related to child growth and development, (ii) increased death, disease and injuries from heat waves, floods, storms, fires and droughts, (iii) increased cardio-respiratory morbidity and mortality associated with ground-level ozone. While IPCC also projects fewer deaths from cold, this positive effect is far outweighed by the negative ones.

Growing awareness of the consequences of human-caused climate change triggers anxiety and feelings of helplessness [136–137]. Children, already susceptible to age-related insecurities, face additional destabilizing insecurities from questions about how they will cope with future climate change [138–139]. Exposure to media ensures that children cannot escape hearing that their future and that of other species is at stake, and that the window of opportunity to avoid dramatic climate impacts is closing. The psychological health of our children is a priority, but denial of the truth exposes our children to even greater risk.

Health impacts of climate change are in addition to direct effects of air and water pollution. A clear illustration of direct effects of fossil fuels on human health was provided by an inadvertent experiment in China during the 1950–1980 period of central planning, when free coal for winter heating was provided to North China but not to the rest of the country. Analysis of the impact was made [140] using the most comprehensive data file ever compiled on mortality and air pollution in any developing country. A principal conclusion was that the 500 million residents of North China experienced during the 1990s a loss of more than 2.5 billion life years owing to the added air pollution, and an average reduction in life expectancy of 5.5 years. The degree of air pollution in China exceeded that in most of the world, yet

assessments of total health effects must also include other fossil fuel caused air and water pollutants, as discussed in the following section on ecology and the environment.

The Text S1 has further discussion of health impacts of climate change.

Ecology and the Environment

The ecological impact of fossil fuel mining increases as the largest, easiest to access, resources are depleted [141]. A constant fossil fuel production rate requires increasing energy input, but also use of more land, water, and diluents, with the production of more waste [142]. The increasing ecological and environmental impact of a given amount of useful fossil fuel energy is a relevant consideration in assessing alternative energy strategies.

Coal mining has progressively changed from predominantly underground mining to surface mining [143], including mountaintop removal with valley fill, which is now widespread in the Appalachian ecoregion in the United States. Forest cover and topsoil are removed, explosives are used to break up rocks to access coal, and the excess rock is pushed into adjacent valleys, where it buries existing streams. Burial of headwater streams causes loss of ecosystems that are important for nutrient cycling and production of organic matter for downstream food webs [144]. The surface alterations lead to greater storm runoff [145] with likely impact on downstream flooding. Water emerging from valley fills contain toxic solutes that have been linked to declines in watershed biodiversity [146]. Even with mine-site reclamation intended to restore pre-mined surface conditions, mine-derived chemical constituents are found in domestic well water [147]. Reclaimed areas, compared with unmined areas, are found to have increased soil density with decreased organic and nutrient content, and with reduced water infiltration rates [148]. Reclaimed areas have been found to produce little if any regrowth of woody vegetation even after 15 years [149], and, although this deficiency might be addressed via more effective reclamation methods, there remains a likely significant loss of carbon storage [149].

Oil mining has an increasing ecological footprint per unit delivered energy because of the decreasing size of new fields and their increased geographical dispersion; transit distances are greater and wells are deeper, thus requiring more energy input [145]. Useful quantitative measures of the increasing ecological impacts are provided by the history of oil development in Alberta, Canada for production of both conventional oil and tar sands development. The area of land required per barrel of produced oil increased by a factor of 12 between 1955 and 2006 [150] leading to ecosystem fragmentation by roads and pipelines needed to support the wells [151]. Additional escalation of the mining impact occurs as conventional oil mining is supplanted by tar sands development, with mining and land disturbance from the latter producing land use-related greenhouse gas emissions as much as 23 times greater than conventional oil production per unit area [152], but with substantial variability and uncertainty [152–153]. Much of the tar sands bitumen is extracted through surface mining that removes the "overburden" (i.e., boreal forest ecosystems) and tar sand from large areas to a depth up to 100 m, with ecological impacts downstream and in the mined area [154]. Although mined areas are supposed to be reclaimed, as in the case of mountaintop removal, there is no expectation that the ecological value of reclaimed areas will be equivalent to predevelopment condition [141,155]. Landscape changes due to tar sands mining and reclamation cause a large loss of peatland and stored carbon, while also significantly reducing carbon sequestration potential [156]. Lake sediment cores document increased chemical pollution of ecosystems during the past several decades traceable to tar sands development [157] and snow and water samples indicate that recent levels of numerous pollutants exceeded local and national criteria for protection of aquatic organisms [158].

Gas mining by unconventional means has rapidly expanded in recent years, without commensurate understanding of the ecological, environmental and human health consequences [159]. The predominant approach is hydraulic fracturing ("fracking") of deep shale formations via injection of millions of gallons of water, sand and toxic chemicals under pressure, thus liberating methane [155,160]. A large fraction of the injected water returns to the surface as wastewater containing high concentrations of heavy metals, oils, greases and soluble organic compounds [161]. Management of this wastewater is a major technical challenge, especially because the polluted waters can continue to backflow from the wells for many years [161]. Numerous instances of groundwater and river contamination have been cited [162]. High levels of methane leakage from fracking have been found [163], as well as nitrogen oxides and volatile organic compounds [159]. Methane leaks increase the climate impact of shale gas, but whether the leaks are sufficient to significantly alter the climate forcing by total natural gas development is uncertain [164]. Overall, environmental and ecologic threats posed by unconventional gas extraction are uncertain because of limited research, however evidence for groundwater pollution on both local and river basin scales is a major concern [165].

Today, with cumulative carbon emissions ~370 GtC from all fossil fuels, we are at a point of severely escalating ecological and environmental impacts from fossil fuel use and fossil fuel mining, as is apparent from the mountaintop removal for coal, tar sands extraction of oil, and fracking for gas. The ecological and environmental implications of scenarios with carbon emissions of 1000 GtC or greater, as discussed below, would be profound and should influence considerations of appropriate energy strategies.

Summary: Climate Impacts

Climate impacts accompanying global warming of 2°C or more would be highly deleterious. Already there are numerous indications of substantial effects in response to warming of the past few decades. That warming has brought global temperature close to if not slightly above the prior range of the Holocene. We conclude that an appropriate target would be to keep global temperature at a level within or close to the Holocene range. Global warming of 2°C would be well outside the Holocene range and far into the dangerous range.

Transient Climate Change

We must quantitatively relate fossil fuel emissions to global temperature in order to assess how rapidly fossil fuel emissions must be phased down to stay under a given temperature limit. Thus we must deal with both a transient carbon cycle and transient global climate change.

Global climate fluctuates stochastically and also responds to natural and human-made climate forcings [1,166]. Forcings, measured in W/m^2 averaged over the globe, are imposed perturbations of Earth's energy balance caused by changing forcing agents such as solar irradiance and human-made greenhouse gases (GHGs). CO_2 accounts for more than 80% of the added GHG forcing in the past 15 years [64,167] and, if fossil fuel emissions continue at a high level, CO_2 will be the dominant driver of future global temperature change.

We first define our method of calculating atmospheric CO_2 as a function of fossil fuel emissions. We then define our assumptions

Exhibit 2 to Declaration of Dr. James E. Hansen

Exhibit A 50

about the potential for drawing down atmospheric CO_2 via reforestation and increase of soil carbon, and we define fossil fuel emission reduction scenarios that we employ in our study. Finally we describe all forcings employed in our calculations of global temperature and the method used to simulate global temperature.

Carbon Cycle and Atmospheric CO_2

The carbon cycle defines the fate of CO_2 injected into the air by fossil fuel burning [1,168] as the additional CO_2 distributes itself over time among surface carbon reservoirs: the atmosphere, ocean, soil, and biosphere. We use the dynamic-sink pulse-response function version of the well-tested Bern carbon cycle model [169], as described elsewhere [54,170].

Specifically, we solve equations 3–6, 16–17, A.2.2, and A.3 of Joos et al. [169] using the same parameters and assumptions therein, except that initial (1850) atmospheric CO_2 is assumed to be 285.2 ppm [167]. Historical fossil fuel CO_2 emissions are from Boden et al. [5]. This Bern model incorporates non-linear ocean chemistry feedbacks and CO_2 fertilization of the terrestrial biosphere, but it omits climate-carbon feedbacks, e.g., assuming static global climate and ocean circulation. Therefore our results should be regarded as conservative, especially for scenarios with large emissions.

A pulse of CO_2 injected into the air decays by half in about 25 years as CO_2 is taken up by the ocean, biosphere and soil, but nearly one-fifth is still in the atmosphere after 500 years (Fig. 4A). Eventually, over hundreds of millennia, weathering of rocks will deposit all of this initial CO_2 pulse on the ocean floor as carbonate sediments [168].

Under equilibrium conditions a negative CO_2 pulse, i.e., artificial extraction and storage of some CO_2 amount, decays at about the same rate as a positive pulse (Fig. 4A). Thus if it is decided in the future that CO_2 must be extracted from the air and removed from the carbon cycle (e.g., by storing it underground or in carbonate bricks), the impact on atmospheric CO_2 amount will diminish in time. This occurs because carbon is exchanged among the surface carbon reservoirs as they move toward an equilibrium distribution, and thus, e.g., CO_2 out-gassing by the ocean can offset some of the artificial drawdown. The CO_2 extraction required to reach a given target atmospheric CO_2 level therefore depends on the prior emission history and target timeframe, but the amount that must be extracted substantially exceeds the net reduction of the atmospheric CO_2 level that will be achieved. We clarify this matter below by means of specific scenarios for capture of CO_2.

It is instructive to see how fast atmospheric CO_2 declines if fossil fuel emissions are instantly terminated (Fig. 4B). Halting emissions in 2015 causes CO_2 to decline to 350 ppm at century's end (Fig. 4B). A 20 year delay in halting emissions has CO_2 returning to 350 ppm at about 2300. With a 40 year delay, CO_2 does not return to 350 ppm until after 3000. These results show how difficult it is to get back to 350 ppm if emissions continue to grow for even a few decades.

These results emphasize the urgency of initiating emissions reduction [171]. As discussed above, keeping global climate close to the Holocene range requires a long-term atmospheric CO_2 level of about 350 ppm or less, with other climate forcings similar to today's levels. If emissions reduction had begun in 2005, reduction at 3.5%/year would have achieved 350 ppm at 2100. Now the requirement is at least 6%/year. Delay of emissions reductions until 2020 requires a reduction rate of 15%/year to achieve 350 ppm in 2100. If we assume only 50 GtC reforestation, and begin emissions reduction in 2013, the required reduction rate becomes about 9%/year.

Reforestation and Soil Carbon

Of course fossil fuel emissions will not suddenly terminate. Nevertheless, it is not impossible to return CO_2 to 350 ppm this century. Reforestation and increase of soil carbon can help draw down atmospheric CO_2. Fossil fuels account for ~80% of the CO_2 increase from preindustrial time, with land use/deforestation accounting for 20% [1,170,172–173]. Net deforestation to date is estimated to be 100 GtC (gigatons of carbon) with ±50% uncertainty [172].

Complete restoration of deforested areas is unrealistic, yet 100 GtC carbon drawdown is conceivable because: (1) the human-enhanced atmospheric CO_2 level increases carbon uptake by some vegetation and soils, (2) improved agricultural practices can convert agriculture from a CO_2 ource into a CO_2 sink [174], (3) biomass-burning power plants with CO_2 capture and storage can contribute to CO_2 drawdown.

Forest and soil storage of 100 GtC is challenging, but has other benefits. Reforestation has been successful in diverse places [175]. Minimum tillage with biological nutrient recycling, as opposed to plowing and chemical fertilizers, could sequester 0.4–1.2 GtC/year [176] while conserving water in soils, building agricultural resilience to climate change, and increasing productivity especially in smallholder rain-fed agriculture, thereby reducing expansion of agriculture into forested ecosystems [177–178]. Net tropical deforestation may have decreased in the past decade [179], but because of extensive deforestation in earlier decades [170,172–173,180–181] there is a large amount of land suitable for reforestation [182].

Use of bioenergy to draw down CO_2 should employ feedstocks from residues, wastes, and dedicated energy crops that do not compete with food crops, thus avoiding loss of natural ecosystems and cropland [183–185]. Reforestation competes with agricultural land use; land needs could decline by reducing use of animal products, as livestock now consume more than half of all crops [186].

Our reforestation scenarios assume that today's net deforestation rate (~1 GtC/year; see [54]) will stay constant until 2020, then linearly decrease to zero by 2030, followed by sinusoidal 100 GtC biospheric carbon storage over 2031–2080. Alternative timings do not alter conclusions about the potential to achieve a given CO_2 level such as 350 ppm.

Emission Reduction Scenarios

A 6%/year decrease of fossil fuel emissions beginning in 2013, with 100 GtC reforestation, achieves a CO_2 decline to 350 ppm near the end of this century (Fig. 5A). Cumulative fossil fuel emissions in this scenario are ~129 GtC from 2013 to 2050, with an additional 14 GtC by 2100. If our assumed land use changes occur a decade earlier, CO_2 returns to 350 ppm several years earlier; however that has negligible effect on the maximum global temperature calculated below.

Delaying fossil fuel emission cuts until 2020 (with 2%/year emissions growth in 2012–2020) causes CO_2 to remain above 350 ppm (with associated impacts on climate) until 2300 (Fig. 5B). If reductions are delayed until 2030 or 2050, CO_2 remains above 350 ppm or 400 ppm, respectively, until well after 2500.

We conclude that it is urgent that large, long-term emission reductions begin soon. Even if a 6%/year reduction rate and 500 GtC are not achieved, it makes a huge difference when reductions begin. There is no practical justification for why emissions necessarily must even approach 1000 GtC.

Climate Forcings

Atmospheric CO_2 and other GHGs have been well-measured for the past half century, allowing accurate calculation of their climate forcing. The growth rate of the GHG forcing has declined

moderately since its peak values in the 1980s, as the growth rate of CH_4 and chlorofluorocarbons has slowed [187]. Annual changes of CO_2 are highly correlated with the El Niño cycle (Fig. 6). Two strong La Niñas in the past five years have depressed CO_2 growth as well as the global warming rate (Fig. 3). The CO_2 growth rate and warming rate can be expected to increase as we move into the next El Niño, with the CO_2 growth already reaching 3 ppm/year in mid-2013 [188]. The CO_2 climate forcing does not increase as rapidly as the CO_2 amount because of partial saturation of CO_2 absorption bands [75]. The GHG forcing is now increasing at a rate of almost 0.4 W/m^2 per decade [187].

Solar irradiance variations are sometimes assumed to be the most likely natural driver of climate change. Solar irradiance has been measured from satellites since the late 1970s (Fig. 7). These data are from a composite of several satellite-measured time series. Data through 28 February 2003 are from [189] and Physikalisch Meteorologisches Observatorium Davos, World Radiation Center. Subsequent update is from University of Colorado Solar Radiation & Climate Experiment (SORCE). Data sets are concatenated by matching the means over the first 12 months of SORCE data. Monthly sunspot numbers (Fig. 7) support the conclusion that the solar irradiance in the current solar cycle is significantly lower than in the three preceding solar cycles. Amplification of the direct solar forcing is conceivable, e.g., through effects on ozone or atmospheric condensation nuclei, but empirical data place a factor of two upper limit on the amplification, with the most likely forcing in the range 100–120% of the directly measured solar irradiance change [64].

Recent reduced solar irradiance (Fig. 7) may have decreased the forcing over the past decade by about half of the full amplitude of measured irradiance variability, thus yielding a negative forcing of, say, − 0.12 W/m^2. This compares with a decadal increase of the GHG forcing that is positive and about three times larger in magnitude. Thus the solar forcing is not negligible and might partially account for the slowdown in global warming in the past decade [17]. However, we must (1) compare the solar forcing with the net of other forcings, which enhances the importance of solar change, because the net forcing is smaller than the GHG forcing, and (2) consider forcing changes on longer time scales, which greatly diminishes the importance of solar change, because solar variability is mainly oscillatory.

Human-made tropospheric aerosols, which arise largely from fossil fuel use, cause a substantial negative forcing. As noted above, two independent analyses [64,72] yield a total (direct plus indirect) aerosol forcing in the past decade of about −1.5 W/m^2, half the magnitude of the GHG forcing and opposite in sign. That empirical aerosol forcing assessment for the past decade is consistent with the climate forcings scenario (Fig. 8) that we use for the past century in the present and prior studies [64,190]. Supplementary Table S1 specifies the historical forcings and Table S2 gives several scenarios for future forcings.

Future Climate Forcings

Future global temperature change should depend mainly on atmospheric CO_2, at least if fossil fuel emissions remain high. Thus to provide the clearest picture of the CO_2 effect, we approximate the net future change of human-made non-CO_2 forcings as zero and we exclude future changes of natural climate forcings, such as solar irradiance and volcanic aerosols. Here we discuss possible effects of these approximations.

Uncertainties in non-CO_2 forcings concern principally solar, aerosol and other GHG forcings. Judging from the sunspot numbers (Fig. 7B and [191]) for the past four centuries, the current solar cycle is almost as weak as the Dalton Minimum of the late 18th century. Conceivably irradiance could decline further to the level of the Maunder Minimum of the late 17th century [192–193]. For our simulation we choose an intermediate path between recovery to the level before the current solar cycle and decline to a still lower level. Specifically, we keep solar irradiance fixed at the reduced level of 2010, which is probably not too far off in either direction. Irradiance in 2010 is about 0.1 W/m^2 less than the mean of the prior three solar cycles, a decrease of forcing that

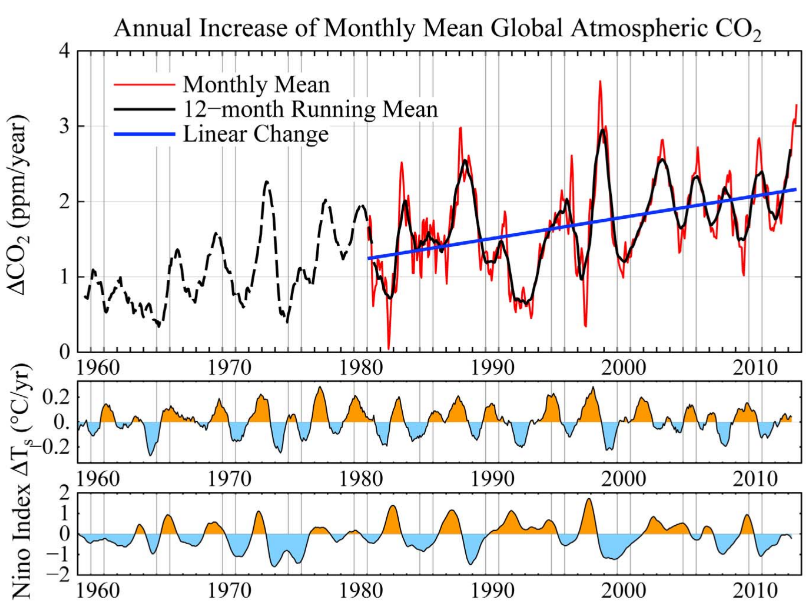


Figure 6. Annual increase of CO_2 based on data from the NOAA Earth System Research Laboratory [188]. Prior to 1981 the CO_2 change is based on only Mauna Loa, Hawaii. Temperature changes in lower diagram are 12-month running means for the globe and Niño3.4 area [16].
doi:10.1371/journal.pone.0081648.g006

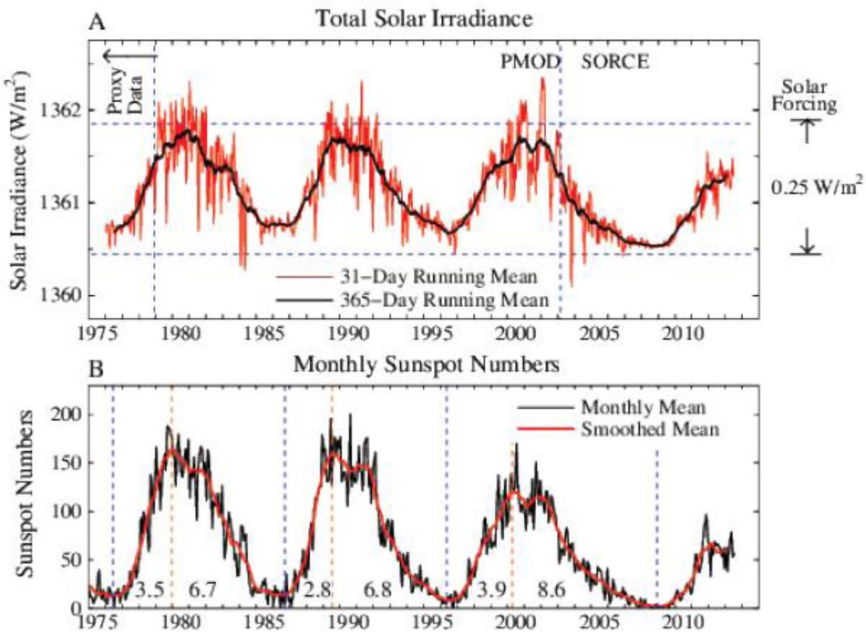


Figure 7. Solar irradiance and sunspot number in the era of satellite data (see text). Left scale is the energy passing through an area perpendicular to Sun-Earth line. Averaged over Earth's surface the absorbed solar energy is ~240 W/m^2, so the full amplitude of measured solar variability is ~0.25 W/m^2.
doi:10.1371/journal.pone.0081648.g007

would be restored by the CO_2 increase within 3–4 years at its current growth rate. Extensive simulations [17,194] confirm that the effect of solar variability is small compared with GHGs if CO_2 emissions continue at a high level. However, solar forcing can affect the magnitude and detection of near-term warming. Also, if rapidly declining GHG emissions are achieved, changes of solar forcing will become relatively more important.

Aerosols present a larger uncertainty. Expectations of decreases in large source regions such as China [195] may be counteracted by aerosol increases other places as global population continues to increase. Our assumption of unchanging human-made aerosols could be substantially off in either direction. For the sake of interpreting on-going and future climate change it is highly desirable to obtain precise monitoring of the global aerosol forcing [73].

Non-CO_2 GHG forcing has continued to increase at a slow rate since 1995 (Fig. 6 in [64]). A desire to constrain climate change may help reduce emissions of these gases in the future. However, it will be difficult to prevent or fully offset positive forcing from increasing N_2O, as its largest source is associated with food production and the world's population is continuing to rise.

On the other hand, we are also probably underestimating a negative aerosol forcing, e.g., because we have not included future volcanic aerosols. Given the absence of large volcanic eruptions in the past two decades (the last one being Mount Pinatubo in 1991), multiple volcanic eruptions would cause a cooling tendency [196] and reduce heat storage in the ocean [197].

Overall, we expect the errors due to our simple approximation of non-CO_2 forcings to be partially off-setting. Specifically, we have likely underestimated a positive forcing by non-CO_2 GHGs, while also likely underestimating a negative aerosol forcing.

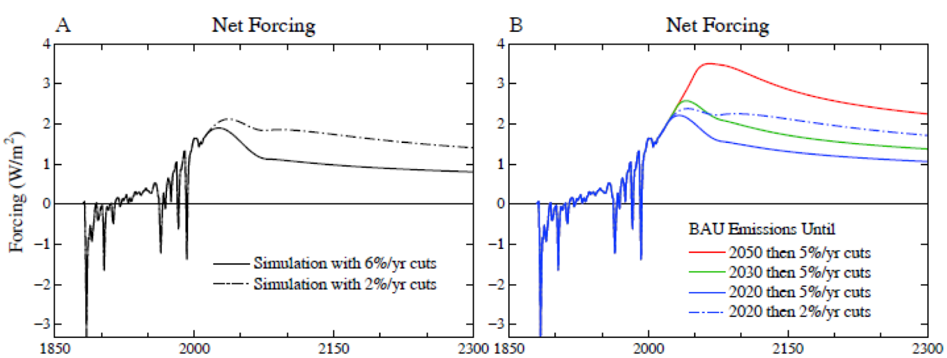


Figure 8. Climate forcings employed in our six main scenarios. Forcings through 2010 are as in [64].
doi:10.1371/journal.pone.0081648.g008

Exhibit 2 to Declaration of Dr. James E. Hansen
Exhibit A 53

Note that uncertainty in forcings is partly obviated via the focus on Earth's energy imbalance in our analysis. The planet's energy imbalance is an integrative quantity that is especially useful for a case in which some of the forcings are uncertain or unmeasured. Earth's measured energy imbalance includes the effects of all forcings, whether they are measured or not.

Simulations of Future Global Temperature

We calculate global temperature change for a given CO_2 scenario using a climate response function (Table S3) that accurately replicates results from a global climate model with sensitivity 3°C for doubled CO_2 [64]. A best estimate of climate sensitivity close to 3°C for doubled CO_2 has been inferred from paleoclimate data [51–52]. This empirical climate sensitivity is generally consistent with that of global climate models [1], but the empirical approach makes the inferred high sensitivity more certain and the quantitative evaluation more precise. Because this climate sensitivity is derived from empirical data on how Earth responded to past changes of boundary conditions, including atmospheric composition, our conclusions about limits on fossil fuel emissions can be regarded as largely independent of climate models.

The detailed temporal and geographical response of the climate system to the rapid human-made change of climate forcings is not well-constrained by empirical data, because there is no faithful paleoclimate analog. Thus climate models necessarily play an important role in assessing practical implications of climate change. Nevertheless, it is possible to draw important conclusions with transparent computations. A simple response function (Green's function) calculation [64] yields an estimate of global mean temperature change in response to a specified time series for global climate forcing. This approach accounts for the delayed response of the climate system caused by the large thermal inertia of the ocean, yielding a global mean temporal response in close accord with that obtained from global climate models.

Tables S1 and S2 in Supporting Information give the forcings we employ and Table S3 gives the climate response function for our Green's function calculation, defined by equation 2 of [64]. The Green's function is driven by the net forcing, which, with the response function, is sufficient information for our results to be reproduced. However, we also include the individual forcings in Table S1, in case researchers wish to replace specific forcings or use them for other purposes.

Simulated global temperature (Fig. 9) is for CO_2 scenarios of Fig. 5. Peak global warming is ~1.1°C, declining to less than 1°C by mid-century, if CO_2 emissions are reduced 6%/year beginning in 2013. In contrast, warming reaches 1.5°C and stays above 1°C until after 2400 if emissions continue to increase until 2030, even though fossil fuel emissions are phased out rapidly (5%/year) after 2030 and 100 GtC reforestation occurs during 2030–2080. If emissions continue to increase until 2050, simulated warming exceeds 2°C well into the 22nd century.

Increased global temperature persists for many centuries after the climate forcing declines, because of the thermal inertia of the ocean [198]. Some temperature reduction is possible if the climate forcing is reduced rapidly, before heat has penetrated into the deeper ocean. Cooling by a few tenths of a degree in Fig. 9 is a result mainly of the 100 GtC biospheric uptake of CO_2 during 2030–2080. Note the longevity of the warming, especially if emissions reduction is as slow as 2%/year, which might be considered to be a rapid rate of reduction.

The temporal response of the real world to the human-made climate forcing could be more complex than suggested by a simple response function calculation, especially if rapid emissions growth continues, yielding an unprecedented climate forcing scenario. For example, if ice sheet mass loss becomes rapid, it is conceivable that the cold fresh water added to the ocean could cause regional surface cooling [199], perhaps even at a point when sea level rise has only reached a level of the order of a meter [200]. However, any uncertainty in the surface thermal response this century due to such phenomena has little effect on our estimate of the dangerous level of emissions. The long lifetime of the fossil fuel carbon in the climate system and the persistence of ocean warming for millennia [201] provide sufficient time for the climate system to achieve full response to the fast feedback processes included in the 3°C climate sensitivity.

Indeed, the long lifetime of fossil fuel carbon in the climate system and persistence of the ocean warming ensure that "slow" feedbacks, such as ice sheet disintegration, changes of the global vegetation distribution, melting of permafrost, and possible release of methane from methane hydrates on continental shelves, would also have time to come into play. Given the unprecedented rapidity of the human-made climate forcing, it is difficult to establish how soon slow feedbacks will become important, but clearly slow feedbacks should be considered in assessing the "dangerous" level of global warming, as discussed in the next section.

Danger of Initiating Uncontrollable Climate Change

Our calculated global warming as a function of CO_2 amount is based on equilibrium climate sensitivity 3°C for doubled CO_2. That is the central climate sensitivity estimate from climate models [1], and it is consistent with climate sensitivity inferred from Earth's climate history [51–52]. However, this climate sensitivity includes only the effects of fast feedbacks of the climate system, such as water vapor, clouds, aerosols, and sea ice. Slow feedbacks, such as change of ice sheet area and climate-driven changes of greenhouse gases, are not included.

Slow Climate Feedbacks and Irreversible Climate Change

Excluding slow feedbacks was appropriate for simulations of the past century, because we know the ice sheets were stable then and our climate simulations used observed greenhouse gas amounts that included any contribution from slow feedbacks. However, we must include slow feedbacks in projections of warming for the 21st century and beyond. Slow feedbacks are important because they affect climate sensitivity and because their instigation is related to the danger of passing "points of no return", beyond which irreversible consequences become inevitable, out of humanity's control.

Antarctic and Greenland ice sheets present the danger of change with consequences that are irreversible on time scales important to society [1]. These ice sheets required millennia to grow to their present sizes. If ice sheet disintegration reaches a point such that the dynamics and momentum of the process take over, at that point reducing greenhouse gases may be unable to prevent major ice sheet mass loss, sea level rise of many meters, and worldwide loss of coastal cities – a consequence that is irreversible for practical purposes. Interactions between the ocean and ice sheets are particularly important in determining ice sheet changes, as a warming ocean can melt the ice shelves, the tongues of ice that extend from the ice sheets into the ocean and buttress the large land-based ice sheets [92,202–203]. Paleoclimate data for sea level change indicate that sea level changed at rates of the order of a meter per century [81–83], even at times when the forcings driving climate change were far weaker than the human-

Exhibit 2 to Declaration of Dr. James E. Hansen

Exhibit A 54

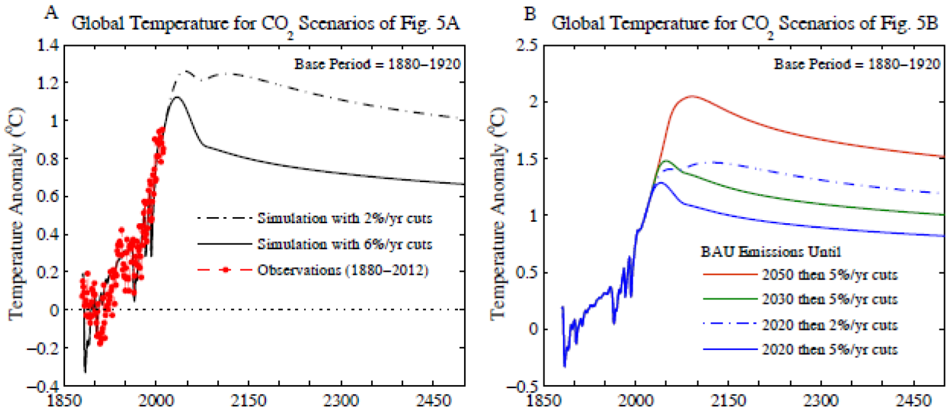


Figure 9. Simulated global temperature relative to 1880–1920 mean for CO_2 scenarios of Figure 5.
doi:10.1371/journal.pone.0081648.g009

made forcing. Thus, because ocean warming is persistent for centuries, there is a danger that large irreversible change could be initiated by excessive ocean warming.

Paleoclimate data are not as helpful for defining the likely rate of sea level rise in coming decades, because there is no known case of growth of a positive (warming) climate forcing as rapid as the anthropogenic change. The potential for unstable ice sheet disintegration is controversial, with opinion varying from likely stability of even the (marine) West Antarctic ice sheet [94] to likely rapid non-linear response extending up to multi-meter sea level rise [97–98]. Data for the modern rate of annual ice sheet mass changes indicate an accelerating rate of mass loss consistent with a mass loss doubling time of a decade or less (Fig. 10). However, we do not know the functional form of ice sheet response to a large persistent climate forcing. Longer records are needed for empirical assessment of this ostensibly nonlinear behavior.

Greenhouse gas amounts in the atmosphere, most importantly CO_2 and CH_4, change in response to climate change, i.e., as a feedback, in addition to the immediate gas changes from human-caused emissions. As the ocean warms, for example, it releases CO_2 to the atmosphere, with one principal mechanism being the simple fact that the solubility of CO_2 decreases as the water temperature rises [204]. We also include in the category of slow feedbacks the global warming spikes, or "hyperthermals", that have occurred a number of times in Earth's history during the course of slower global warming trends. The mechanisms behind these hyperthermals are poorly understood, as discussed below, but they are characterized by the injection into the surface climate system of a large amount of carbon in the form of CH_4 and/or CO_2 on the time scale of a millennium [205–207]. The average rate of injection of carbon into the climate system during these hyperthermals was slower than the present human-made injection of fossil fuel carbon, yet it was faster than the time scale for removal of carbon from the surface reservoirs via the weathering process [3,208], which is tens to hundreds of thousands of years.

Methane hydrates – methane molecules trapped in frozen water molecule cages in tundra and on continental shelves – and organic matter such as peat locked in frozen soils (permafrost) are likely mechanisms in the past hyperthermals, and they provide another climate feedback with the potential to amplify global warming if large scale thawing occurs [209–210]. Paleoclimate data reveal instances of rapid global warming, as much as 5–6°C, as a sudden additional warming spike during a longer period of gradual warming [see Text S1]. The candidates for the carbon injected into the climate system during those warmings are methane hydrates on continental shelves destabilized by sea floor warming [211] and carbon released from frozen soils [212]. As for the present, there are reports of methane release from thawing permafrost on land [213] and from sea-bed methane hydrate deposits [214], but amounts so far are small and the data are snapshots that do not prove that there is as yet a temporal increase of emissions.

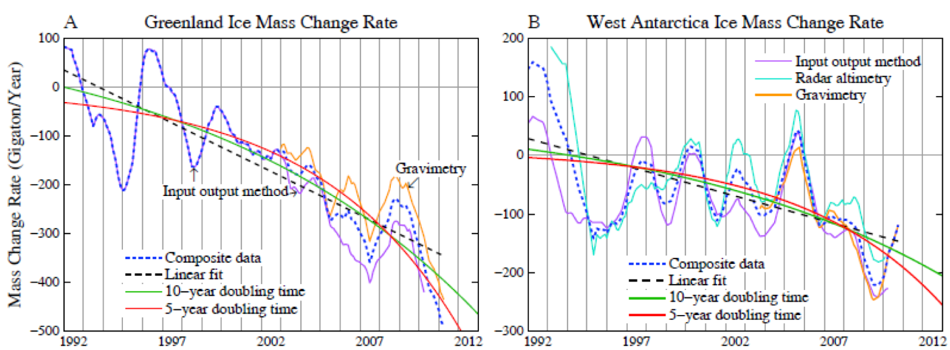


Figure 10. Annual Greenland and West Antarctic ice mass changes as estimated via alternative methods. Data were read from Figure 4 of Shepherd et al. [23] and averaged over the available records.
doi:10.1371/journal.pone.0081648.g010

There is a possibility of rapid methane hydrate or permafrost emissions in response to warming, but that risk is largely unquantified [215]. The time needed to destabilize large methane hydrate deposits in deep sediments is likely millennia [215]. Smaller but still large methane hydrate amounts below shallow waters as in the Arctic Ocean are more vulnerable; the methane may oxidize to CO_2 in the water, but it will still add to the long-term burden of CO_2 in the carbon cycle. Terrestrial permafrost emissions of CH_4 and CO_2 likely can occur on a time scale of a few decades to several centuries if global warming continues [215]. These time scales are within the lifetime of anthropogenic CO_2, and thus these feedbacks must be considered in estimating the dangerous level of global warming. Because human-made warming is more rapid than natural long-term warmings in the past, there is concern that methane hydrate or peat feedbacks could be more rapid than the feedbacks that exist in the paleoclimate record.

Climate model studies and empirical analyses of paleoclimate data can provide estimates of the amplification of climate sensitivity caused by slow feedbacks, excluding the singular mechanisms that caused the hyperthermal events. Model studies for climate change between the Holocene and the Pliocene, when Earth was about 3°C warmer, find that slow feedbacks due to changes of ice sheets and vegetation cover amplified the fast feedback climate response by 30–50% [216]. These same slow feedbacks are estimated to amplify climate sensitivity by almost a factor of two for the climate change between the Holocene and the nearly ice-free climate state that existed 35 million years ago [54].

Implication for Carbon Emissions Target

Evidence presented under Climate Impacts above makes clear that 2°C global warming would have consequences that can be described as disastrous. Multiple studies [12,198,201] show that the warming would be very long lasting. The paleoclimate record and changes underway in the Arctic and on the Greenland and Antarctic ice sheets with only today's warming imply that sea level rise of several meters could be expected. Increased climate extremes, already apparent at 0.8°C warming [46], would be more severe. Coral reefs and associated species, already stressed with current conditions [40], would be decimated by increased acidification, temperature and sea level rise. More generally, humanity and nature, the modern world as we know it, is adapted to the Holocene climate that has existed more than 10,000 years. Warming of 1°C relative to 1880–1920 keeps global temperature close to the Holocene range, but warming of 2°C, to at least the Eemian level, could cause major dislocations for civilization.

However, distinctions between pathways aimed at ~1°C and 2°C warming are much greater and more fundamental than the numbers 1°C and 2°C themselves might suggest. These fundamental distinctions make scenarios with 2°C or more global warming far more dangerous; so dangerous, we suggest, that aiming for the 2°C pathway would be foolhardy.

First, most climate simulations, including ours above and those of IPCC [1], do not include slow feedbacks such as reduction of ice sheet size with global warming or release of greenhouse gases from thawing tundra. These exclusions are reasonable for a ~1°C scenario, because global temperature barely rises out of the Holocene range and then begins to subside. In contrast, global warming of 2°C or more is likely to bring slow feedbacks into play. Indeed, it is slow feedbacks that cause long-term climate sensitivity to be high in the empirical paleoclimate record [51–52]. The lifetime of fossil fuel CO_2 in the climate system is so long that it must be assumed that these slow feedbacks will occur if temperature rises well above the Holocene range.

Second, scenarios with 2°C or more warming necessarily imply expansion of fossil fuels into sources that are harder to get at, requiring greater energy using extraction techniques that are increasingly invasive, destructive and polluting. Fossil fuel emissions through 2012 total ~370 GtC (Fig. 2). If subsequent emissions decrease 6%/year, additional emissions are ~130 GtC, for a total ~500 GtC fossil fuel emissions. This 130 GtC can be obtained mainly from the easily extracted conventional oil and gas reserves (Fig. 2), with coal use rapidly phased out and unconventional fossil fuels left in the ground. In contrast, 2°C scenarios have total emissions of the order of 1000 GtC. The required additional fossil fuels will involve exploitation of tar sands, tar shale, hydrofracking for oil and gas, coal mining, drilling in the Arctic, Amazon, deep ocean, and other remote regions, and possibly exploitation of methane hydrates. Thus 2°C scenarios result in more CO_2 per unit useable energy, release of substantial CH_4 via the mining process and gas transportation, and release of CO_2 and other gases via destruction of forest "overburden" to extract subterranean fossil fuels.

Third, with our ~1°C scenario it is more likely that the biosphere and soil will be able to sequester a substantial portion of the anthropogenic fossil fuel CO_2 carbon than in the case of 2°C or more global warming. Empirical data for the CO_2 "airborne fraction", the ratio of observed atmospheric CO_2 increase divided by fossil fuel CO_2 emissions, show that almost half of the emissions is being taken up by surface (terrestrial and ocean) carbon reservoirs [187], despite a substantial but poorly measured contribution of anthropogenic land use (deforestation and agriculture) to airborne CO_2 [179,216]. Indeed, uptake of CO_2 by surface reservoirs has at least kept pace with the rapid growth of emissions [187]. Increased uptake in the past decade may be a consequence of a reduced rate of deforestation [217] and fertilization of the biosphere by atmospheric CO_2 and nitrogen deposition [187]. With the stable climate of the ~1°C scenario it is plausible that major efforts in reforestation and improved agricultural practices [15,173,175–177], with appropriate support provided to developing countries, could take up an amount of carbon comparable to the 100 GtC in our ~1°C scenario. On the other hand, with warming of 2°C or more, carbon cycle feedbacks are expected to lead to substantial additional atmospheric CO_2 [218–219], perhaps even making the Amazon rainforest a source of CO_2 [219–220].

Fourth, a scenario that slows and then reverses global warming makes it possible to reduce other greenhouse gases by reducing their sources [75,221]. The most important of these gases is CH_4, whose reduction in turn reduces tropospheric O_3 and stratospheric H_2O. In contrast, chemistry modeling and paleoclimate records [222] show that trace gases increase with global warming, making it unlikely that overall atmospheric CH_4 will decrease even if a decrease is achieved in anthropogenic CH_4 sources. Reduction of the amount of atmospheric CH_4 and related gases is needed to counterbalance expected forcing from increasing N_2O and decreasing sulfate aerosols.

Now let us compare the 1°C (500 GtC fossil fuel emissions) and the 2°C (1000 GtC fossil fuel emissions) scenarios. Global temperature in 2100 would be close to 1°C in the 500 GtC scenario, and it is less than 1°C if 100 GtC uptake of carbon by the biosphere and soil is achieved via improved agricultural and forestry practices (Fig. 9). In contrast, the 1000 GtC scenario, although nominally designed to yield a fast-feedback climate response of ~ 2°C, would yield a larger eventual warming because of slow feedbacks, probably at least 3°C.

Exhibit 2 to Declaration of Dr. James E. Hansen

Exhibit A 56

Danger of Uncontrollable Consequences

Inertia of the climate system reduces the near-term impact of human-made climate forcings, but that inertia is not necessarily our friend. One implication of the inertia is that climate impacts "in the pipeline" may be much greater than the impacts that we presently observe. Slow climate feedbacks add further danger of climate change running out of humanity's control. The response time of these slow feedbacks is uncertain, but there is evidence that some of these feedbacks already are underway, at least to a minor degree. Paleoclimate data show that on century and millennial time scales the slow feedbacks are predominately amplifying feedbacks.

The inertia of energy system infrastructure, i.e., the time required to replace fossil fuel energy systems, will make it exceedingly difficult to avoid a level of atmospheric CO_2 that would eventually have highly undesirable consequences. The danger of uncontrollable and irreversible consequences necessarily raises the question of whether it is feasible to extract CO_2 from the atmosphere on a large enough scale to affect climate change.

Carbon Extraction

We have shown that extraordinarily rapid emission reductions are needed to stay close to the 1°C scenario. In absence of extraordinary actions, it is likely that growing climate disruptions will lead to a surge of interest in "geo-engineering" designed to minimize human-made climate change [223]. Such efforts must remove atmospheric CO_2, if they are to address direct CO_2 effects such as ocean acidification as well as climate change. Schemes such as adding sulfuric acid aerosols to the stratosphere to reflect sunlight [224], an attempt to mask one pollutant with another, is a temporary band-aid for a problem that will last for millennia; besides it fails to address ocean acidification and may have other unintended consequences [225].

Potential for Carbon Extraction

At present there are no proven technologies capable of large-scale air capture of CO_2. It has been suggested that, with strong research and development support and industrial scale pilot projects sustained over decades, costs as low as ~\$500/tC may be achievable [226]. Thermodynamic constraints [227] suggest that this cost estimate may be low. An assessment by the American Physical Society [228] argues that the lowest currently achievable cost, using existing approaches, is much greater (\$600/tCO_2 or \$2200/tC).

The cost of capturing 50 ppm of CO_2, at \$500/tC (~\$135/tCO_2), is ~\$50 trillion (1 ppm CO_2 is ~2.12 GtC), but more than \$200 trillion for the price estimate of the American Physical Society study. Moreover, the resulting atmospheric CO_2 reduction will ultimately be less than 50 ppm for the reasons discussed above. For example, let us consider the scenario of Fig. 5B in which emissions continue to increase until 2030 before decreasing at 5%/year – this scenario yields atmospheric CO_2 of 410 ppm in 2100. Using our carbon cycle model we calculate that if we extract 100 ppm of CO_2 from the air over the period 2030–2100 (10/7 ppm per year), say storing that CO_2 in carbonate bricks, the atmospheric CO_2 amount in 2100 will be reduced 52 ppm to 358 ppm, i.e., the reduction of airborne CO_2 is about half of the amount extracted from the air and stored. The estimated cost of this 52 ppm CO_2 reduction is \$100–400 trillion.

The cost of CO_2 capture and storage conceivably may decline in the future. Yet the practicality of carrying out such a program with alacrity in response to a climate emergency is dubious. Thus it may be appropriate to add a CO_2 removal cost to the current price of fossil fuels, which would both reduce ongoing emissions and provide resources for future cleanup.

Responsibility for Carbon Extraction

We focus on fossil fuel carbon, because of its long lifetime in the carbon cycle. Reversing the effects of deforestation is also important and there will need to be incentives to achieve increased carbon storage in the biosphere and soil, but the crucial requirement now is to limit the amount of fossil fuel carbon in the air.

The high cost of carbon extraction naturally raises the question of responsibility for excess fossil fuel CO_2 in the air. China has the largest CO_2 emissions today (Fig. 11A), but the global warming effect is closely proportional to cumulative emissions [190]. The United States is responsible for about one-quarter of cumulative emissions, with China next at about 10% (Fig. 11B). Cumulative responsibilities change rather slowly (compare Fig. 10 of 190). Estimated per capita emissions (Fig. 12) are based on population estimates for 2009–2011.

Various formulae might be devised to assign costs of CO_2 air capture, should removal prove essential for maintaining acceptable climate. For the sake of estimating the potential cost, let us assume that it proves necessary to extract 100 ppm of CO_2 (yielding a reduction of airborne CO_2 of about 50 ppm) and let us assign each country the responsibility to clean up its fraction of cumulative emissions. Assuming a cost of \$500/tC (~\$135/tCO_2) yields a cost of \$28 trillion for the United States, about \$90,000 per individual. Costs would be slightly higher for a UK citizen, but less for other nations (Fig. 12B).

Cost of CO_2 capture might decline, but the cost estimate used is more than a factor of four smaller than estimated by the American Physical Society [228] and 50 ppm is only a moderate reduction. The cost should also include safe permanent disposal of the captured CO_2, which is a substantial mass. For the sake of scaling the task, note that one GtC, made into carbonate bricks, would produce the volume of ~3000 Empire State buildings or ~1200 Great Pyramids of Giza. Thus the 26 ppm assigned to the United States, if made into carbonate bricks, would be equivalent to the stone in 165,000 Empire State buildings or 66,000 Great Pyramids of Giza. This is not intended as a practical suggestion: carbonate bricks are not a good building material, and the transport and construction costs would be additional.

The point of this graphic detail is to make clear the magnitude of the cleanup task and potential costs, if fossil fuel emissions continue unabated. More useful and economic ways of removing CO_2 may be devised with the incentive of a sufficient carbon price. For example, a stream of pure CO_2 becomes available for capture and storage if biomass is used as the fuel for power plants or as feedstock for production of liquid hydrocarbon fuels. Such clean energy schemes and improved agricultural and forestry practices are likely to be more economic than direct air capture of CO_2, but they must be carefully designed to minimize undesirable impacts and the amount of CO_2 that can be extracted on the time scale of decades will be limited, thus emphasizing the need to limit the magnitude of the cleanup task.

Policy Implications

Human-made climate change concerns physical sciences, but leads to implications for policy and politics. Conclusions from the physical sciences, such as the rapidity with which emissions must be reduced to avoid obviously unacceptable consequences and the long lag between emissions and consequences, lead to implications in social sciences, including economics, law and ethics. Intergov-

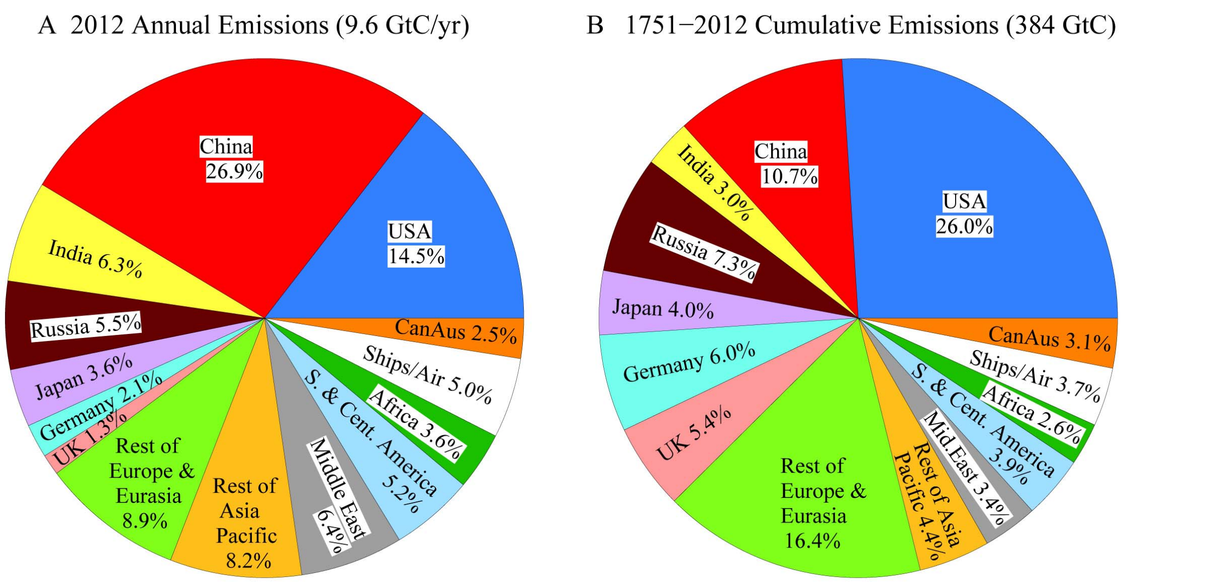


Figure 11. Fossil fuel CO_2 emissions. (A) 2012 emissions by source region, and (B) cumulative 1751–2012 emissions. Results are an update of Fig. 10 of [190] using data from [5].
doi:10.1371/journal.pone.0081648.g011

ernmental climate assessments [1,14] purposely are not policy prescriptive. Yet there is also merit in analysis and discussion of the full topic through the objective lens of science, i.e., "connecting the dots" all the way to policy implications.

Energy and Carbon Pathways: A Fork in the Road

The industrial revolution began with wood being replaced by coal as the primary energy source. Coal provided more concentrated energy, and thus was more mobile and effective. We show data for the United States (Fig. 13) because of the availability of a long data record that includes wood [229]. More limited global records yield a similar picture [Fig. 14], the largest difference being global coal now at ~30% compared with ~20% in the United States. Economic progress and wealth generation were further spurred in the twentieth century by expansion into liquid and gaseous fossil fuels, oil and gas being transported and burned more readily than coal. Only in the latter part of the twentieth century did it become clear that long-lived combustion products from fossil fuels posed a global climate threat, as formally acknowledged in the 1992 Framework Convention on Climate Change [6]. However, efforts to slow emissions of the principal atmospheric gas driving climate change, CO_2, have been ineffectual so far (Fig. 1).

Consequently, at present, as the most easily extracted oil and gas reserves are being depleted, we stand at a fork in the road to our energy and carbon future. Will we now feed our energy needs by pursuing difficult to extract fossil fuels, or will we pursue energy policies that phase out carbon emissions, moving on to the post fossil fuel era as rapidly as practical?

This is not the first fork encountered. Most nations agreed to the Framework Convention on Climate Change in 1992 [6]. Imagine if a bloc of countries favoring action had agreed on a common gradually rising carbon fee collected within each of country at domestic mines and ports of entry. Such nations might place equivalent border duties on products from nations not having a carbon fee and they could rebate fees to their domestic industry for export products to nations without an equivalent carbon fee. The legality of such a border tax adjustment under international trade law is untested, but is considered to be plausibly consistent with trade principles [230]. As the carbon fee gradually rose and as additional nations, for their own benefit, joined this bloc of nations, development of carbon-free energies and energy efficiency would have been spurred. If the carbon fee had begun in 1995, we

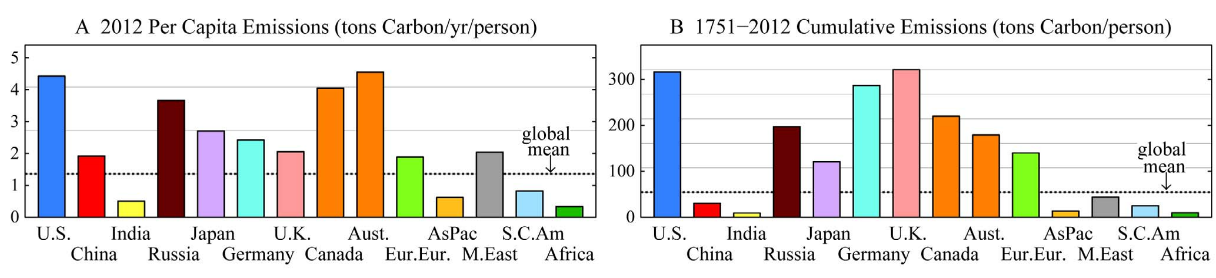


Figure 12. Per capita fossil fuel CO_2 emissions. Countries, regions and data sources are the same as in Fig. 11. Horizontal lines are the global mean and multiples of the global mean.
doi:10.1371/journal.pone.0081648.g012

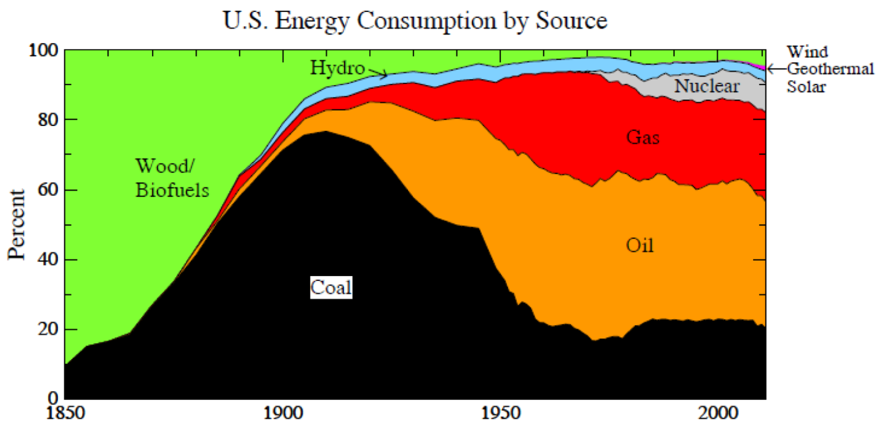


Figure 13. United States energy consumption [229].
doi:10.1371/journal.pone.0081648.g013

calculate that global emissions would have needed to decline 2.1%/year to limit cumulative fossil fuel emissions to 500 GtC. A start date of 2005 would have required a reduction of 3.5%/year for the same result.

The task faced today is more difficult. Emissions reduction of 6%/year and 100 GtC storage in the biosphere and soils are needed to get CO_2 back to 350 ppm, the approximate requirement for restoring the planet's energy balance and stabilizing climate this century. Such a pathway is exceedingly difficult to achieve, given the current widespread absence of policies to drive rapid movement to carbon-free energies and the lifetime of energy infrastructure in place.

Yet we suggest that a pathway is still conceivable that could restore planetary energy balance on the century time scale. That path requires policies that spur technology development and provide economic incentives for consumers and businesses such that social tipping points are reached where consumers move rapidly to energy conservation and low carbon energies. Moderate overshoot of required atmospheric CO_2 levels can possibly be counteracted via incentives for actions that more-or-less naturally sequester carbon. Developed countries, responsible for most of the excess CO_2 in the air, might finance extensive efforts in developing countries to sequester carbon in the soil and in forest regrowth on marginal lands as described above. Burning sustainably designed biofuels in power plants, with the CO_2 captured and sequestered, would also help draw down atmospheric CO_2. This pathway would need to be taken soon, as the magnitude of such carbon extractions is likely limited and thus not a solution to unfettered fossil fuel use.

The alternative pathway, which the world seems to be on now, is continued extraction of all fossil fuels, including development of unconventional fossil fuels such as tar sands, tar shale, hydrofracking to extract oil and gas, and exploitation of methane hydrates. If that path (with 2%/year growth) continues for 20 years and is then followed by 3%/year emission reduction from 2033 to 2150, we find that fossil fuel emissions in 2150 would total 1022 GtC. Extraction of the excess CO_2 from the air in this case would be very expensive and perhaps implausible, and warming of the ocean and resulting climate impacts would be practically irreversible.

Economic Implications: Need for a Carbon Fee

The implication is that the world must move rapidly to carbon-free energies and energy efficiency, leaving most remaining fossil fuels in the ground, if climate is to be kept close to the Holocene range and climate disasters averted. Is rapid change possible?

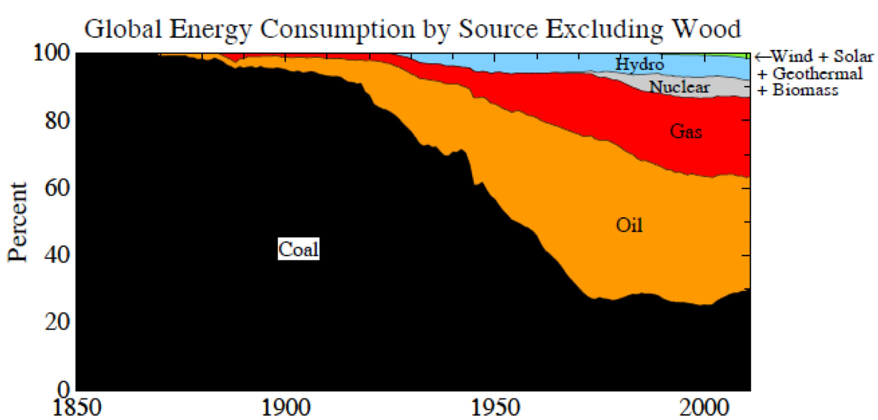


Figure 14. World energy consumption for indicated fuels, which excludes wood [4].
doi:10.1371/journal.pone.0081648.g014

Exhibit 2 to Declaration of Dr. James E. Hansen
Exhibit A 59

The potential for rapid change can be shown by examples. A basic requirement for phasing down fossil fuel emissions is abundant carbon-free electricity, which is the most rapidly growing form of energy and also has the potential to provide energy for transportation and heating of buildings. In one decade (1977–1987), France increased its nuclear power production 15-fold, with the nuclear portion of its electricity increasing from 8% to 70% [231]. In one decade (2001–2011) Germany increased the non-hydroelectric renewable energy portion of its electricity from 4% to 19%, with fossil fuels decreasing from 63% to 61% (hydroelectric decreased from 4% to 3% and nuclear power decreased from 29% to 18%) [231].

Given the huge task of replacing fossil fuels, contributions are surely required from energy efficiency, renewable energies, and nuclear power, with the mix depending on local preferences. Renewable energy and nuclear power have been limited in part by technical challenges. Nuclear power faces persistent concerns about safety, nuclear waste, and potential weapons proliferation, despite past contributions to mortality prevention and climate change mitigation [232]. Most renewable energies tap diffuse intermittent sources often at a distance from the user population, thus requiring large-scale energy storage and transport. Developing technologies can ameliorate these issues, as discussed below. However, apparent cost is the constraint that prevents nuclear and renewable energies from fully supplanting fossil fuel electricity generation.

Transition to a post-fossil fuel world of clean energies will not occur as long as fossil fuels appear to the investor and consumer to be the cheapest energy. Fossil fuels are cheap only because they do not pay their costs to society and receive large direct and indirect subsidies [233]. Air and water pollution from fossil fuel extraction and use have high costs in human health, food production, and natural ecosystems, killing more than 1,000,000 people per year and affecting the health of billions of people [232,234], with costs borne by the public. Costs of climate change and ocean acidification, already substantial and expected to grow considerably [26,235], also are borne by the public, especially by young people and future generations.

Thus the essential underlying policy, albeit not sufficient, is for emissions of CO_2 to come with a price that allows these costs to be internalized within the economics of energy use. Because so much energy is used through expensive capital stock, the price should rise in a predictable way to enable people and businesses to efficiently adjust lifestyles and investments to minimize costs. Reasons for preference of a carbon fee or tax over cap-and-trade include the former's simplicity and relative ease of becoming global [236]. A near-global carbon tax might be achieved, e.g., via a bi-lateral agreement between China and the United States, the greatest emitters, with a border duty imposed on products from nations without a carbon tax, which would provide a strong incentive for other nations to impose an equivalent carbon tax. The suggestion of a carbon fee collected from fossil fuel companies with all revenues distributed to the public on a per capita basis [237] has received at least limited support [238].

Economic analyses indicate that a carbon price fully incorporating environmental and climate damage would be high [239]. The cost of climate change is uncertain to a factor of 10 or more and could be as high as ~\$1000/tCO_2 [235,240]. While the imposition of such a high price on carbon emissions is outside the realm of short-term political feasibility, a price of that magnitude is not required to engender a large change in emissions trajectory.

An economic analysis indicates that a tax beginning at \$15/tCO_2 and rising \$10/tCO_2 each year would reduce emissions in the U.S. by 30% within 10 years [241]. Such a reduction is more than 10 times as great as the carbon content of tar sands oil carried by the proposed Keystone XL pipeline (830,000 barrels/day) [242]. Reduced oil demand would be nearly six times the pipeline capacity [241], thus the carbon fee is far more effective than the proposed pipeline.

A rising carbon fee is the *sine qua non* for fossil fuel phase out, but not enough by itself. Investment is needed in RD&D (research, development and demonstration) to help renewable energies and nuclear power overcome obstacles limiting their contributions. Intermittency of solar and wind power can be alleviated with advances in energy storage, low-loss smart electric grids, and electrical vehicles interacting with the grid. Most of today's nuclear power plants have half-century-old technology with light-water reactors [243] utilizing less than 1% of the energy in the nuclear fuel and leaving unused fuel as long-lived nuclear "waste" requiring sequestration for millennia. Modern light-water reactors can employ convective cooling to eliminate the need for external cooling in the event of an anomaly such as an earthquake. However, the long-term future of nuclear power will employ "fast" reactors, which utilize ~99% of the nuclear fuel and can "burn" nuclear waste and excess weapons material [243]. It should be possible to reduce the cost of nuclear power via modular standard reactor design, but governments need to provide a regulatory environment that supports timely construction of approved designs. RD&D on carbon capture and storage (CCS) technology is needed, especially given our conclusion that the current atmospheric CO_2 level is already in the dangerous zone, but continuing issues with CCS technology [7,244] make it inappropriate to construct fossil fuel power plants with a promise of future retrofit for carbon capture. Governments should support energy planning for housing and transportation, energy and carbon efficiency requirements for buildings, vehicles and other manufactured products, and climate mitigation and adaptation in undeveloped countries.

Economic efficiency would be improved by a rising carbon fee. Energy efficiency and alternative low-carbon and no-carbon energies should be allowed to compete on an equal footing, without subsidies, and the public and business community should be made aware that the fee will continually rise. The fee for unconventional fossil fuels, such as oil from tar sands and gas from hydrofracking, should include carbon released in mining and refining processes, e.g., methane leakage in hydrofracking [245–249]. If the carbon fee rises continually and predictably, the resulting energy transformations should generate many jobs, a welcome benefit for nations still suffering from long-standing economic recession. Economic modeling shows that about 60% of the public, especially low-income people, would receive more money via a per capita 100% dispersal of the collected fee than they would pay because of increased prices [241].

Fairness: Intergenerational Justice and Human Rights

Relevant fundamentals of climate science are clear. The physical climate system has great inertia, which is due especially to the thermal inertia of the ocean, the time required for ice sheets to respond to global warming, and the longevity of fossil fuel CO_2 in the surface carbon reservoirs (atmosphere, ocean, and biosphere). This inertia implies that there is additional climate change "in the pipeline" even without further change of atmospheric composition. Climate system inertia also means that, if large-scale climate change is allowed to occur, it will be exceedingly long-lived, lasting for many centuries.

One implication is the likelihood of intergenerational effects, with young people and future generations inheriting a situation in which grave consequences are assured, practically out of their

control, but not of their doing. The possibility of such intergenerational injustice is not remote – it is at our doorstep now. We have a planetary climate crisis that requires urgent change to our energy and carbon pathway to avoid dangerous consequences for young people and other life on Earth.

Yet governments and industry are rushing into expanded use of fossil fuels, including unconventional fossil fuels such as tar sands, tar shale, shale gas extracted by hydrofracking, and methane hydrates. How can this course be unfolding despite knowledge of climate consequences and evidence that a rising carbon price would be economically efficient and reduce demand for fossil fuels? A case has been made that the absence of effective governmental leadership is related to the effect of special interests on policy, as well as to public relations efforts by organizations that profit from the public's addiction to fossil fuels [237,250].

The judicial branch of governments may be less subject to pressures from special financial interests than the executive and legislative branches, and the courts are expected to protect the rights of all people, including the less powerful. The concept that the atmosphere is a public trust [251], that today's adults must deliver to their children and future generations an atmosphere as beneficial as the one they received, is the basis for a lawsuit [252] in which it is argued that the U.S. government is obligated to protect the atmosphere from harmful greenhouse gases.

Independent of this specific lawsuit, we suggest that intergenerational justice in this matter derives from fundamental rights of equality and justice. The Universal Declaration of Human Rights [253] declares "All are equal before the law and are entitled without any discrimination to equal protection of the law." Further, to consider a specific example, the United States Constitution provides all citizens "equal protection of the laws" and states that no person can be deprived of "life, liberty or property without due process of law". These fundamental rights are a basis for young people to expect fairness and justice in a matter as essential as the condition of the planet they will inhabit. We do not prescribe the legal arguments by which these rights can be achieved, but we maintain that failure of governments to effectively address climate change infringes on fundamental rights of young people.

Ultimately, however, human-made climate change is more a matter of morality than a legal issue. Broad public support is probably needed to achieve the changes needed to phase out fossil fuel emissions. As with the issue of slavery and civil rights, public recognition of the moral dimensions of human-made climate change may be needed to stir the public's conscience to the point of action.

A scenario is conceivable in which growing evidence of climate change and recognition of implications for young people lead to massive public support for action. Influential industry leaders, aware of the moral issue, may join the campaign to phase out emissions, with more business leaders becoming supportive as they recognize the merits of a rising price on carbon. Given the relative ease with which a flat carbon price can be made international [236], a rapid global emissions phasedown is feasible. As fossil fuels are made to pay their costs to society, energy efficiency and clean energies may reach tipping points and begin to be rapidly adopted.

Our analysis shows that a set of actions exists with a good chance of averting "dangerous" climate change, if the actions begin now. However, we also show that time is running out. Unless a human "tipping point" is reached soon, with implementation of effective policy actions, large irreversible climate changes will become unavoidable. Our parent's generation did not know that their energy use would harm future generations and other life on the planet. If we do not change our course, we can only pretend that we did not know.

Discussion

We conclude that an appropriate target is to keep global temperature within or close to the temperature range in the Holocene, the interglacial period in which civilization developed. With warming of 0.8°C in the past century, Earth is just emerging from that range, implying that we need to restore the planet's energy balance and curb further warming. A limit of approximately 500 GtC on cumulative fossil fuel emissions, accompanied by a net storage of 100 GtC in the biosphere and soil, could keep global temperature close to the Holocene range, assuming that the net future forcing change from other factors is small. The longevity of global warming (Fig. 9) and the implausibility of removing the warming if it is once allowed to penetrate the deep ocean emphasize the urgency of slowing emissions so as to stay close to the 500 GtC target.

Fossil fuel emissions of 1000 GtC, sometimes associated with a 2°C global warming target, would be expected to cause large climate change with disastrous consequences. The eventual warming from 1000 GtC fossil fuel emissions likely would reach well over 2°C, for several reasons. With such emissions and temperature tendency, other trace greenhouse gases including methane and nitrous oxide would be expected to increase, adding to the effect of CO_2. The global warming and shifting climate zones would make it less likely that a substantial increase in forest and soil carbon could be achieved. Paleoclimate data indicate that slow feedbacks would substantially amplify the 2°C global warming. It is clear that pushing global climate far outside the Holocene range is inherently dangerous and foolhardy.

The fifth IPCC assessment Summary for Policymakers [14] concludes that to achieve a 50% chance of keeping global warming below 2°C equivalent CO_2 emissions should not exceed 1210 GtC, and after accounting for non-CO_2 climate forcings this limit on CO_2 emissions becomes 840 GtC. The existing drafts of the fifth IPCC assessment are not yet approved for comparison and citation, but the IPCC assessment is consistent with studies of Meinshausen et al. [254] and Allen et al. [13], hereafter M2009 and A2009, with which we can make comparisons. We will also compare our conclusions with those of McKibben [255]. M2009 and A2009 appear together in the same journal with the two lead authors on each paper being co-authors on the other paper. McKibben [255], published in a popular magazine, uses quantitative results of M2009 to conclude that most remaining fossil fuel reserves must be left in the ground, if global warming this century is to be kept below 2°C. McKibben [255] has been very successful in drawing public attention to the urgency of rapidly phasing down fossil fuel emissions.

M2009 use a simplified carbon cycle and climate model to make a large ensemble of simulations in which principal uncertainties in the carbon cycle, radiative forcings, and climate response are allowed to vary, thus yielding a probability distribution for global warming as a function of time throughout the 21st century. M2009 use this distribution to infer a limit on total (fossil fuel+net land use) carbon emissions in the period 2000–2049 if global warming in the 21st century is to be kept below 2°C at some specified probability. For example, they conclude that the limit on total 2000–2049 carbon emissions is 1440 $GtCO_2$ (393 GtC) to achieve a 50% chance that 21st century global warming will not exceed 2°C.

A2009 also use a large ensemble of model runs, varying uncertain parameters, and conclude that total (fossil fuel+net land use) carbon emissions of 1000 GtC would most likely yield a peak

Exhibit 2 to Declaration of Dr. James E. Hansen
Exhibit A 61

CO_2-induced warming of 2°C, with 90% confidence that the peak warming would be in the range 1.3–3.9°C. They note that their results are consistent with those of M2009, as the A2009 scenarios that yield 2°C warming have 400–500 GtC emissions during 2000–2049; M2009 find 393 GtC emissions for 2°C warming, but M2009 included a net warming effect of non-CO_2 forcings, while A2009 neglected non-CO_2 forcings.

McKibben [255] uses results of M2009 to infer allowable fossil fuel emissions up to 2050 if there is to be an 80% chance that maximum warming in the 21st century will not exceed 2°C above the pre-industrial level. M2009 conclude that staying under this 2°C limit with 80% probability requires that 2000–2049 emissions must be limited to 656 $GtCO_2$ (179 GtC) for 2007–2049. McKibben [255] used this M2009 result to determine a remaining carbon budget (at a time not specified exactly) of 565 $GtCO_2$ (154 GtC) if warming is to stay under 2°C. Let us update this analysis to the present: fossil fuel emissions in 2007–2012 were 51 GtC [5], so, assuming no net emissions from land use in these few years, the M2009 study implies that the remaining budget at the beginning of 2013 was 128 GtC.

Thus, coincidentally, the McKibben [255] approach via M2009 yields almost exactly the same remaining carbon budget (128 GtC) as our analysis (130 GtC). However, our budget is that required to limit warming to about 1°C (there is a temporary maximum during this century at about 1.1–1.2°C, Fig. 9), while McKibben [255] is allowing global warming to reach 2°C, which we have concluded would be a disaster scenario! This apparently vast difference arises from three major factors.

First, we assumed that reforestation and improved agricultural and forestry practices can suck up the net land use carbon of the past. We estimate net land use emissions as 100 GtC, while M2009 have land use emissions almost twice that large (~180 GtC). We argue elsewhere (see section 14 in Supporting Information of [54]) that the commonly employed net land use estimates [256] are about a factor of two larger than the net land use carbon that is most consistent with observed CO_2 history. However, we need not resolve that long-standing controversy here. The point is that, to make the M2009 study equivalent to ours, negative land use emissions must be included in the 21st century equal to earlier positive land use emissions.

Second, we have assumed that future net change of non-CO_2 forcings will be zero, while M2009 have included significant non-CO_2 forcings. In recent years non-CO_2 GHGs have provided about 20% of the increase of total GHG climate forcing.

Third, our calculations are for a single fast-feedback equilibrium climate sensitivity, 3°C for doubled CO_2, which we infer from paleoclimate data. M2009 use a range of climate sensitivities to compute a probability distribution function for expected warming, and then McKibben [255] selects the carbon emission limit that keeps 80% of the probability distribution below 2°C.

The third factor is a matter of methodology, but one to be borne in mind. Regarding the first two factors, it may be argued that our scenario is optimistic. That is true, but both goals, extracting 100 GtC from the atmosphere via improved forestry and agricultural practices (with possibly some assistance from CCS technology) and limiting additional net change of non-CO_2 forcings to zero, are feasible and probably much easier than the principal task of limiting additional fossil fuel emissions to 130 GtC.

We noted above that reforestation and improving agricultural and forestry practices that store more carbon in the soil make sense for other reasons. Also that task is made easier by the excess CO_2 in the air today, which causes vegetation to take up CO_2 more efficiently. Indeed, this may be the reason that net land use emissions seem to be less than is often assumed.

As for the non-CO_2 forcings, it is noteworthy that greenhouse gases controlled by the Montreal Protocol are now decreasing, and recent agreement has been achieved to use the Montreal Protocol to phase out production of some additional greenhouse gases even though those gases do not affect the ozone layer. The most important non-CO_2 forcing is methane, whose increases in turn cause tropospheric ozone and stratospheric water vapor to increase. Fossil fuel use is probably the largest source of methane [1], so if fossil fuel use begins to be phased down, there is good basis to anticipate that all three of these greenhouse gases could decrease, because of the approximate 10-year lifetime of methane.

As for fossil fuel CO_2 emissions, considering the large, long-lived fossil fuel infrastructure in place, the science is telling us that policy should be set to reduce emissions as rapidly as possible. The most fundamental implication is the need for an across-the-board rising fee on fossil fuel emissions in order to allow true free market competition from non-fossil energy sources. We note that biospheric storage should not be allowed to offset further fossil fuel emissions. Most fossil fuel carbon will remain in the climate system more than 100,000 years, so it is essential to limit the emission of fossil fuel carbon. It will be necessary to have incentives to restore biospheric carbon, but these must be accompanied by decreased fossil fuel emissions.

A crucial point to note is that the three tasks [limiting fossil fuel CO_2 emissions, limiting (and reversing) land use emissions, limiting (and reversing) growth of non-CO_2 forcings] are interactive and reinforcing. In mathematical terms, the problem is non-linear. As one of these climate forcings increases, it increases the others. The good news is that, as one of them decreases, it tends to decrease the others. In order to bestow upon future generations a planet like the one we received, we need to win on all three counts, and by far the most important is rapid phasedown of fossil fuel emissions.

It is distressing that, despite the clarity and imminence of the danger of continued high fossil fuel emissions, governments continue to allow and even encourage pursuit of ever more fossil fuels. Recognition of this reality and perceptions of what is "politically feasible" may partially account for acceptance of targets for global warming and carbon emissions that are well into the range of "dangerous human-made interference" with climate. Although there is merit in simply chronicling what is happening, there is still opportunity for humanity to exercise free will. Thus our objective is to define what the science indicates is needed, not to assess political feasibility. Further, it is not obvious to us that there are physical or economic limitations that prohibit fossil fuel emission targets far lower than 1000 GtC, even targets closer to 500 GtC. Indeed, we suggest that rapid transition off fossil fuels would have numerous near-term and long-term social benefits, including improved human health and outstanding potential for job creation.

A world summit on climate change will be held at United Nations Headquarters in September 2014 as a preliminary to negotiation of a new climate treaty in Paris in late 2015. If this treaty is analogous to the 1997 Kyoto Protocol [257], based on national targets for emission reductions and cap-and-trade-with-offsets emissions trading mechanisms, climate deterioration and gross intergenerational injustice will be practically guaranteed. The palpable danger that such an approach is conceivable is suggested by examination of proposed climate policies of even the most forward-looking of nations. Norway, which along with the other Scandinavian countries has been among the most ambitious and successful of all nations in reducing its emissions, nevertheless approves expanded oil drilling in the Arctic and development of tar sands as a majority owner of Statoil [258–259]. Emissions

foreseen by the Energy Perspectives of Statoil [259], if they occur, would approach or exceed 1000 GtC and cause dramatic climate change that would run out of control of future generations. If, in contrast, leading nations agree in 2015 to have internal rising fees on carbon with border duties on products from nations without a carbon fee, a foundation would be established for phaseover to carbon free energies and stable climate.

Supporting Information

Table S1
(ODS)

Table S2
(ODS)

Table S3
(ODS)

Text S1
(DOC)

Acknowledgments

We greatly appreciate the assistance of editor Juan A. Añel in achieving requisite form and clarity for publication. The paper is dedicated to Paul Epstein, a fervent defender of the health of humans and the environment, who graciously provided important inputs to this paper while battling late stages of non-Hodgkin's lymphoma. We thank David Archer, Inez Fung, Charles Komanoff and two anonymous referees for perceptive helpful reviews and Mark Chandler, Bishop Dansby, Ian Dunlop, Dian Gaffen Seidel, Edward Greisch, Fred Hendrick, Tim Mock, Ana Prados, Stefan Rahmstorf, Rob Socolow and George Stanford for helpful suggestions on a draft of the paper.

Author Contributions

Conceived and designed the experiments: JH PK MS. Performed the experiments: MS PK. Wrote the paper: JH. Wrote the first draft: JH. All authors made numerous critiques and suggested specific wording and references: JH PK MS VM-D FA DJB PJH OHG SLH CP JR EJR JS PS KS LVS KvS JCZ. Especially: PK MS VM-D.

References

1. Intergovernmental Panel on Climate Change (2007) Climate Change 2007: Physical Science Basis, Solomon, S, Dahe, Q, Manning M, Chen Z, Marquis M, et al., editors. Cambridge Univ. Press: New York 2007; 996 pp.
2. Hansen J, Sato M, Ruedy R, Nazarenko L, Lacis A, et al. (2005) Efficacy of climate forcings. J Geophys Res 110, D18104, doi:10.1029/2005JD005776.
3. Archer D (2005) Fate of fossil fuel CO_2 in geologic time. J Geophys Res 110: C09S05.
4. BP Statistical Review of World Energy 2012 (http://www.bp.com/sectionbodycopy.do?categoryId = 7500&contentId = 7068481).
5. Boden TA, Marland G, Andres RJ (2012) Global, Regional, and National Fossil-Fuel CO_2 Emissions. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A. doi 10.3334/CDIAC/00001_V2012.
6. United Nations Framework Convention on Climate Change (1992) Available: http://www.unfccc.int.
7. Energy Information Administration (EIA) (2011) International Energy Outlook Available: http://www.eia.gov/forecasts/ieo/pdf/0484.Pdf accessed Sept 2011.
8. German Advisory Council on Global Change (GAC)(2011) World in Transition - A Social Contract for Sustainability. Available: http://www.wbgu.de/en/flagship-reports/fr-2011-a-social-contract/. Accessed Oct 2011.
9. Global Energy Assessment (GEA) (2012) Toward a Sustainable Future. Johanson TB, Patwardhan E, Nakićenović N, editors. Cambridge: Cambridge University Press.
10. Randalls S (2010) History of the 2°C climate target. WIREs Clim Change 1, 598–605.
11. Copenhagen Accord (2009) United Nations Framework Convention on Climate Change, Draft decision −/CP.15 FCCC/CP/2009/L.7 18 December 2009.
12. Matthews HD, Gillett NP, Stott PA, Zickfeld K (2009) The proportionality of global warming to cumulative carbon emissions. Nature 459: 829–832.
13. Allen MR, Frame DJ, Huntingford C, Jones CD, Lowe JA, et al. (2009) Warming caused by cumulative carbon emissions towards the trillionth tonne. Nature 458, 1163–1166.
14. Intergovernmental Panel on Climate Change (2013) Approved Summary for Policymakers of full draft report of Climate Change 2013: Physical Science Basis, Stocker T, Dahe Q, Plattner G-K, coordinating lead authors, available: http://www.ipcc.ch/report/ar5/wg1/#.UlCweRCvHMM.
15. Intergovernmental Panel on Climate Change (2007) Climate Change 2007: Mitigation of Climate Change. Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA, editors. Cambridge: Cambridge University Press.
16. Hansen J, Ruedy R, Sato M, Lo K (2010) Global Surface Temperature Change. Rev Geophys 48: RG4004.
17. Meehl GA, Arblaster JM, Marsh DR (2013) Could a future "Grand Solar Minimum" like the Maunder Minimum stop global warming? Geophys Res Lett 40, 1789–1793.
18. Kosaka Y, Xie SP (2013) Recent global-warming hiatus tied to equatorial Pacific surface cooling. Nature published online 28 August doi:10.1038/nature12534.
19. Intergovernmental Panel on Climate Change (2001) Climate Change 2001: The Scientific Basis. Houghton JT, MacCarthy JJ, Metz M, editors. Cambridge: Cambridge University Press.
20. Schneider SH, Mastrandrea MD (2005) Probabilistic assessment "dangerous" climate change and emissions pathways. Proc Natl Acad Sci USA 102: 15728–15735.
21. Stroeve JC, Kattsov V, Barrett A, Serreze M, Pavlova T, et al. (2012) Trends in Arctic sea ice extent from CMIP5, CMIP3 and observations. Geophys Res Lett 39: L16502.
22. Rampal P, Weiss J, Dubois C, Campin JM (2011) IPCC climate models do not capture Arctic sea ice drift acceleration: Consequences in terms of projected sea ice thinning and decline. J Geophys Res 116: C00D07.
23. Shepherd A, Ivins ER, Geruo A, Barletta VR, Bentley MJ, et al. (2012) A reconciled estimate of ice-sheet mass balance. Science 338: 1183–1189.
24. Rignot E, Velicogna I, van den Broeke MR, Monaghan A, Lenaerts J (2011) Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise. Geophys Res Lett 38: L05503–L05508.
25. Hanna E, Navarro FJ, Pattyn F,Domingues CM, Fettweis X, et al. (2013) Ice-sheet mass balance and climate change. Nature 498: 51–59.
26. Intergovernmental Panel on Climate Change (2007) Climate Change 2007: Impacts, Adaptation and Vulnerability. Parry, ML, Canziani O, Palutikof J, van der Linden P, Hanson C, editors. Cambridge: Cambridge University Press.
27. Rabatel A, Francou B, Soruco A, Gomez J, Caceres B, et al. (2013) Current state of glaciers in the tropical Andes: a multi-century perspective on glacier evolution and climate change. The Cryosphere 7: 81–102.
28. Sorg A, Bolch T, Stoffel M, Solomina O, Beniston M (2012) Climate change impacts on glaciers and runoff in Tien Shan (Central Asia). Nature Clim Change 2, 725–731.
29. Yao T, Thompson L, Yang W, Yu W, Gao Y, et al. (2012) Differrent glacier status with atmospheric circulations in Tibetan Plateau and surroundings. Nature Clim Change 2, 663–667.
30. Barnett TP, Pierce DW, Hidalgo HG, Bonfils C, Santer BD, et al. (2008) Human-induced changes in the hydrology of the western United States. Science 319: 1080–1083.
31. Kaser G, Grosshauser M, Marzeion B (2010) Contribution potential of glaciers to water availability in different climate regimes. Proc Natl Acad Sci USA 107: 20223–20227.
32. Vergara W, Deeb AM, Valencia AM, Bradley RS, Francou B, et al. (2007) Economic impacts of rapid glacier retreat in the Andes. EOS Trans Amer. Geophys Union 88: 261–268.
33. Held IM, Soden BJ (2006) Robust responses of the hydrological cycle to global warming. J Clim 19: 5686–5699.
34. Seidel DJ, Fu Q, Randel WJ, Reichler TJ (2008) Widening of the tropical belt in a changing climate. Nat Geosci 1: 21–24.
35. Davis SM, Rosenlof KH (2011) A multi-diagnostic intercomparison of tropical width time series using reanalyses and satellite observations. J Clim doi: 10.1175/JCLI-D-1111–00127.00121.
36. Liu J, Song M, Hu Y, Ren X (2012) Changes in the strength and width of the Hadley circulation since 1871. Clim Past 8: 1169–1175.
37. Dai A (2013) Increasing drought under global warming in observations and models. Nature Clim Change 3, 52–58.
38. Westerling AL, Hidalgo HG, Cayan DR, Swetnam TW (2006) Warming and earlier spring increase western US forest wildfire activity. Science 313: 940–943.
39. Bruno JF, Selig ER (2007) Regional decline of coral cover in the Indo-Pacific: timing, extent, and subregional comparisons. Plos One 2: e711.
40. Hoegh-Guldberg O, Mumby PJ, Hooten AJ, Steneck RS, Greenfield P, et al. (2007) Coral reefs under rapid climate change and ocean acidification. Science 318: 1737–1742.
41. Veron JE, Hoegh-Guldberg O, Lenton TM, Lough JM, Obura DO, et al. (2009) The coral reef crisis: The critical importance of <350 ppm CO2. Mar Pollut Bull 58: 1428–1436.

Exhibit 2 to Declaration of Dr. James E. Hansen
Exhibit A 63

42. Parmesan C, Yohe G (2003) A globally coherent fingerprint of climate change impacts across natural systems. Nature 421: 37–42.
43. Parmesan C (2006) Ecological and evolutionary responses to recent climate change. Ann Rev Ecol Evol S 37: 637–669.
44. Poloczanska ES, Brown CJ, Sydeman WJ, Kiessling W, Schoeman DS, et al. (2013) Global imprint of climate change on marine life. Nature Clim Change doi:10.1038/NCLIMATE1958.
45. Rahmstorf S, Coumou D (2011) Increase of extreme events in a warming world. Proc Natl Acad Sci USA 108: 17905–17909.
46. Hansen J, Sato M, Ruedy R (2012) Perception of climate change. Proc Natl Acad Sci USA 109: 14726–14727.
47. Lewis SC, Karoly DJ (2013) Anthropogenic contributions to Australia's record summer temperatures of 2013. Geophys Res Lett (in press).
48. Jouzel J, Masson-Delmotte V, Cattani O, Dreyfus G, Falourd S, et al. (2007) Orbital and millennial Antarctic climate variability over the past 800,000 years. Science 317: 793–796.
49. Masson-Delmotte V, Stenni B, Pol K, Braconnot P, Cattani O, et al. (2010) EPICA Dome C record of glacial and interglacial intensities. Quat Sci Rev 29: 113–128.
50. Zachos J, Pagani M, Sloan L, Thomas E, Billups K (2001) Trends, rhythms, and aberrations in global climate 65 Ma to present. Science 292: 686–693.
51. Rohling EJ, Sluijs A, Dijkstra HA, Kohler P, van de Wal RSW, et al. (2012) Making sense of palaeoclimate sensitivity. Nature 491: 683–691.
52. Hansen J, Sato M, Russell G, Kharecha P (2013) Climate sensitivity, sea level, and atmospheric CO_2. Philos Trans R Soc A 371: 20120294, 2013.
53. Foster GL, Rohling EJ (2013) Relationship between sea level and climate forcing by CO_2 on geological timescales. Proc Natl Acad Sci USA doi:10.1073/pnas.1216073110.
54. Hansen J, Sato M, Kharecha P, Beerling D, Berner R, et al. (2008) Target Atmospheric CO_2: Where Should Humanity Aim? The Open Atmospheric Science Journal 2: 217–231.
55. Marcott SA, Shakun JD, Clark PU, Mix AC (2013) A reconstruction of regional and global temperature for the last 11,300 years. Science 339: 1198–1201.
56. Pagani M, Liu ZH, LaRiviere J, Ravelo AC (2010) High Earth-system climate sensitivity determined from Pliocene carbon dioxide concentrations. Nat Geosci 3: 27–30.
57. Meyssignac B, Cazenave A (2012) Sea level: a review of present-day and recent-past changes and variability. J Geodynamics 58, 96–109.
58. Berger AL (1978) Long term variations of daily insolation and quaternary climate changes. J Atmos Sci 35:2362–2367.
59. Hansen J, Sato M, Kharecha P, Russell G, Lea DW et al. (2007) Climate change and trace gases. Phil Tran Roy Soc 365: 1925–1954.
60. Kohler P, Fischer H, Joos F, Knutti R, Lohmann G, et al. (2010) What caused Earth's temperature variations during the last 800,000 years? Data-based evidence on radiative forcing and constraints on climate sensitivity. Quat Sci Rev 29: 29–145.
61. Masson-Delmotte V, Stenni B, Pol K, Braconnot P, Cattani O, et al. (2010) EPICA Dome C record of glacial and interglacial intensities. Quat Sci Rev 29: 113–128.
62. Rohling EJ, Medina-Elizalde M, Shepherd JG, Siddall M, Stanford JD (2011) Sea surface and high-latitude temperature sensitivity to radiative forcing of climate over several glacial cycles. J Clim doi: 10.1175/2011JCLI4078.1171.
63. Beerling DJ, Royer DL (2011) Convergent Cenozoic CO_2 history. Nat Geosci 4: 418–420.
64. Hansen J, Sato M, Kharecha P, Schuckmann K (2011) Earth's Energy Imbalance and Implications. Atmos Chem Phys 11: 1–29.
65. Levitus S, Antonov JI, Wang J, Delworth TL, Dixon KW, Broccoli AJ (2001) Anthropogenic warming of earth's climate system. Science 292, 267–270.
66. Roemmich D, Gilson J (2009) The 2004–2008 mean and annual cycle of temperature, salinity, and steric height in the global ocean from the Argo Program. Prog Oceanogr 82: 81–100.
67. Lyman JM,Good SA, Gouretski VV, Ishii M, Johnson GC, et al. (2010) Robust warming of the global upper ocean. Nature 465: 334–337.
68. Barker PM, Dunn JR, Domingues CM, Wijffels SE (2011) Pressure Sensor Drifts in Argo and Their Impacts. J Atmos Ocean Tech 28: 1036–1049.
69. Levitus S, Antonov JI, Boyer TP, Baranova OK, Garcia HE, et al. (2012) World ocean heat content and thermosteric sea level change (0–2000 m), 1955–2010, Geophys Res Lett 39, L10603.
70. von Schuckmann K, LeTraon P-Y (2011) How well can we derive Global Ocean Indicators from Argo data? Ocean Sci 7: 783–391.
71. Frohlich C (2006) Solar irradiance variability since 1978. Space Sci Rev 125: 53–65.
72. Murphy DM, Solomon S, Portmann RW, Rosenlof KH, Forster PM, Wong T (2009) An observationally based energy balance for the Earth since 1950. J Geophys Res 114: D17107.
73. Mishchenko MI, Cairns B, Kopp G, Schueler CF, Fafaul BA, et al. (2007) Accurate monitoring of terrestrial aerosols and total solar irradiance: introducing the Glory mission. B Am Meteorol Soc 88: 677–691.
74. Economist (2013) Beijing's air pollution: blackest day. Economist, 14 January 2013. Available at: http://www.economist.com/blogs/analects/2013/01/beijings-air-pollution.
75. Hansen J, Sato M, Ruedy R, Lacis A, Oinas V (2000) Global warming in the twenty-first century: An alternative scenario. Proc Natl Acad Sci USA 97: 9875–9880.
76. Bond T, Doherty SJ, Fahey DW, Forster PM, Berntsen T, et al. (2013) Bounding the role of black carbon in the climate system: a scientific assessment. J Geophys Res (in press).
77. Smith JB, Schneider SH, Oppenheimer M, Yohe GW, Hare W, et al. (2009) Assessing dangerous climate change thorough an update of the Intergovernmental Panel on Climate Change (IPCC) "reasons of concern". Proc Natl Acad Sci USA 106, 4133–4137.
78. Hearty PJ, Hollin JT, Neumann AC, O'Leary MJ, McCulloch M (2007) Global sea-level fluctuations during the Last Interglaciation (MIS 5e). Quaternary Sci Rev 26: 2090–2112.
79. Kopp RE, Simons FJ, Mitrovica JX, Maloof AC, Oppenheimer M (2009) Probabilistic assessment of sea level during the last interglacial stage. Nature 462: 863–867.
80. Dutton A, Lambeck K (2012) Ice volume and sea level during the last interglacial. Science 337: 216−219.
81. Rohling EJ, Grant K, Hemleben C, Siddall M, Hoogakker BAA, et al. (2008) High rates of sea-level rise during the last interglacial period. Nat Geosci 1: 38–42.
82. Thompson WG, Curran HA, Wilson MA, White B (2011) Sea-level oscillations during the last interglacial highstand recorded by Bahamas corals. Nat Geosci 4: 684–687.
83. Blanchon P, Eisenhauer A, Fietzke J, Volker L (2009) Rapid sea-level rise and reef back-stepping at the close of the last interglacial highstand. Nature 458: 881–884.
84. Hearty PJ, Neumann AC (2001) Rapid sea level and climate change at the close of the Last Interglaciation (MIS 5e): evidence from the Bahama Islands. Quaternary Sci Rev 20: 1881–1895.
85. O'Leary MJ, Hearty PJ, Thompson WG, Raymo ME, Mitrovica X, et al. (2013) Ice sheet collapse following a prolonged period of stable sea level during the Last Interglacial. Nature Geosci., published online 28 July. doi:10.1038/NGEO1890.
86. Raymo ME, Mitrovica JX, O'Leary MJ, DeConto RM, Hearty P (2011) Departures from eustasy in Pliocene sea-level records. Nat Geosci 4: 328–332.
87. Naish TR, Wilson G (2009) Constraints on the amplitude of Mid-Pliocene (3.6–2.4 Ma) eustatic sea-level fluctuations from the New Zealand shallow-marine sediment record. Philos Trans R Soc A 367: 169–187.
88. Hill DJ, Haywood DM, Hindmarsh RCM, Valdes PJ (2007) Characterizing ice sheets during the Pliocene: evidence from data and models. In: Williams M, Haywood AM, Gregory J, Schmidt DN, editors. Deep-Time Perspectives on Climate Change: Marrying the Signal from Computer Models and Biological Proxies. London: Micropalaeont Soc Geol Soc. 517–538.
89. Dwyer GS, Chandler MA (2009) Mid-Pliocene sea level and continental ice volume based on coupled benthic Mg/Ca palaeotemperatures and oxygen isotopes. Phil Trans R Soc A 367: 157–168.
90. Rignot E, Bamber JL, van den Broeke MR, Davis C, Li Y, et al. (2008) Recent Antarctic ice mass loss from radar interferometry and regional climate modelling. Nat Geosci 1: 106–110.
91. NEEM community members (2013) Eemian interglacial reconstructed from a Greenland folded ice core. Nature 493: 489–494.
92. Hughes T (1972) Is the West Antarctic ice sheet disintegrating? ISCAP Bulletin, no. 1, Ohio State Univ.
93. Oppenheimer M (1999) Global warming and the stability of the West Antarctic ice sheet. Nature 393: 325–332.
94. Bentley CR (1997) Rapid sea-level rise soon from West Antarctic ice sheet collapse? Science 275: 1077–1078.
95. Vermeer M, Rahmstorf S (2009) Global sea level linked to global temperature. Proc Nat Acad Sci USA 106: 21527–21532.
96. Grinsted A, Moore J, Jevrejeva S (2010) Reconstructing sea level from paleo and projected temperatures 200 to 2100 AD. Clim Dyn 34: 461–472.
97. Hansen JE (2005) A slippery slope: How much global warming constitutes "dangerous anthropogenic interference"? Clim Chg 68: 269–279.
98. Hansen J (2007) Scientific reticence and sea level rise. Env Res Lett 2: 024002.
99. Tedesco M, Fettweis X, Mote T, Wahr J, Alexander P, et al. (2012) Evidence and analysis of 2012 Greenland records from spaceborne observations, a regional climate model and reanalysis data. Cryospre Discuss 6, 4939–4976.
100. Levi BG (2008) Trends in the hydrology of the western US bear the imprint of manmade climate change. Physics Today 61: 16–18.
101. Hansen J, Sato M, Ruedy R, Lo K, Lea DW, et al. (2006) Global temperature change. Proc Natl Acad Sci USA 103: 14288–14293.
102. Burrows MT, Schoeman DS, Buckley LB, Moore P, Poloczanska ES, et al. (2011) The Pace of Shifting Climate in Marine and Terrestrial Ecosystems. Science 334: 652–655.
103. Hoegh-Guldberg O, Bruno JF (2010) The Impact of Climate Change on the World's Marine Ecosystems. Science 328: 1523–1528.
104. Seimon TA, Seimon A, Daszak P, Halloy SRP, Sdchloegel LM, et al. (2007) Upward range extension of Andean anurans and chytridiomycosis to extreme elevations in response to tropical deglaciation. Global Change Biol 13: 288–299.
105. Pounds JA, Fogden MPL, Campbell JH (1999) Biological response to climate change on a tropical mountain. Nature 398: 611–615.

Exhibit 2 to Declaration of Dr. James E. Hansen

Exhibit A 64

106. Pounds JA, Bustamante MR, Coloma LA, Consuegra JA, Fogden MPL, et al. (2006) Widespread amphibian extinctions from epidemic disease driven by global warming. Nature 439: 161–167.
107. Alford RA, Bradfield KS, Richards SJ (2007) Ecology: Global warming and amphibian losses. Nature 447: E3–E4.
108. Rosa ID, Simoncelli F, Fagotti A, Pascolini R (2007) Ecology: The proximate cause of frog declines? Nature 447: E4–E5.
109. Pounds JA, Bustamante MR, Coloma LA, Consuegra JA, Fogden MPL, et al. (2007) Ecology – Pounds et al reply. Nature 447: E5–E6.
110. Mahlstein I, Daniel JS, Solomon S (2013) Pace of shifts in climate regions increases with global temperature. Nature Clim Change doi:10.1038/nclimate1876.
111. Olson S, Hearty P (2010) Predation as the primary selective force in recurrent evolution of gigantism in *Poecilozonites* land snails in Quaternary Bermuda. Biol Lett 6, 807–810.
112. Hearty P, Olson S (2010) Geochronology, biostratigraphy, and chaning shell morphology in the land snail subgenus *Poecilozonites* during the Quaternary of Bermuda. Palaeog Plaeocl Palaeoeco 293, 9–29.
113. Olson S, Hearty P (2003) Probably extirpation of a middle Pleistocene breeding colony of Short-tailed Albatross (*Phoebastria albatrus*) on Bermuda by a +20 m interglacial sea-level rise. Proc Natl Acad Sci USA 100, 12825–12829.
114. Taylor J, Braithwaite C, Peake J, Arnold E (1979) Terrestrial fauna and habitats of Aldabra during the lat Pleistocene. Phil Trans Roy Soc Lon B 286, 47–66.
115. 2010 IUCN Red List of Threatened Species (http://www.iucnredlist.org/details/9010/0).
116. Butchart SHM, Walpole M, Collen B, van Strein A, Scharlemann JPW, et al. (2010) Global biodiversity: indicators of recent declines. Science 328: 1164–1168.
117. Raup DM, Sepkoski JJ (1982) Mass Extinctions in the Marine Fossil Record. Science 215: 1501–1503.
118. Barnosky AD, Matzke N, Tomiya S, Wogan GOU, Swartz B, et al. (2011) Has the Earth's sixth mass extinction already arrived? Nature 471: 51–57.
119. Reaka-Kudla ML (1997) Global biodiversity of coral reefs: a comparison with rainforests. In: Reaka-Kudla ML, Wilson DE, Wilson EO, editors. Biodiversity II: Understanding and Protecting Our Biological Resources. Washington, DC: Joseph Henry Press. 83–108.
120. Caldeira K, Wickett ME (2003) Oceanography: Anthropogenic carbon and ocean pH. Nature 425: 365–365.
121. Raven J, Caldeira K, Elderfield H, Hoegh-Guldberg O, Liss P, et al. (2005) Ocean acidification due to increasing atmospheric carbon dioxide. London: Royal Society.
122. Pelejero C, Calvo E, Hoegh-Guldberg O (2010) Paleo-perspectives on ocean acidification. Trends Ecol Evol 25: 332–344.
123. Hoegh-Guldberg O (1999) Climate change, coral bleaching and the future of the world's coral reefs. Mar Freshwater Res 50: 839–866.
124. De'ath G, Lough JM, Fabricius KE (2009) Declining Coral Calcification on the Great Barrier Reef. Science 323: 116–119.
125. Seager R, Naik N, Vogel L (2012) Does global warming cause intensified interannual hydroclimate variability? J Clim 25: 3355–3372.
126. Held IM, Delworth TL, Lu J, Findell KL, Knutson TR (2005) Simulation of Sahel drought in the 20th and 21st centuries. Proc Natl Acad Sci USA 102:17891–17896.
127. Groisman PY, Knight RW, Easterling DR, Karl TR, Hegerl GC, et al. (2005) Trends in intense precipitation in the climate record. J Clim 18:1326–1350.
128. Alexander LV, Zhang X, Peterson TC, Caesar J, Gleason B, et al. (2006) Global observed changes in daily climate extremes of temperature and precipitation. J Geophys Res 111: D05109.
129. Min SK, Zhang X, Zwiers FW, Hegerl GC (2011) Human contribution to more-intense precipitation extremes. Nature 470:378–381.
130. Dai A (2011) Drought under global warming: a review. WIREs Clim Change 2:45–65.
131. Briffa KR, van der Schrier G, Jones PD (2009) Wet and dry summers in Europe since 1750: evidence of increasing drought. Int J Climatol 29:1894–1905.
132. Sheffield J, Wood EF, Roderick ML (2012) Little change in global drought over the past 60 years. Nature 491: 435–438.
133. Robine JM, Cheung SL, Le Roy S, Van Oyen H, Griffiths C, et al. (2008) Death toll exceeded 70,000 in Europe during the summer of 2003. Cr Biol 331: 171–175.
134. Barriopedro D, Fischer EM, Luterbacher J, Trigo R, Garcia-Herrera R (2011) The Hot Summer of : Redrawing the Temperature Record Map of Europe. Science 332: 220–224.
135. Stott PA, Stone DA, Allen MR (2004) Human contribution to the European heatwave of 2003. Nature 432: 610–614.
136. Fritze JG, Blashki GA, Burke S, Wiseman J (2008) Hope, despair and transformation: climate change and the promotion of mental health and well-being. International J Mantal Health Sys 7:2–13.
137. Searle K, Gow K (2010) Do concerns about climate change lead to distress? International J Clim Change Strat Manag 2: 362–378.
138. Hicks D, Bord A (2001) Learning about global issues: why most educators only make things worse. Envir Education Res 7:413–425.
139. Gottlieb D, Bronstein P (1996) Parent's perceptions of children's worries in a changing world. J Genetic Psychol 157:104–118.
140. Chen Y, Ebenstein A, Greenstone M, Li H (2013) Evidence on the impact of sustained exposure to air pollution on life expectancy from China's Huai River policy. Proc Natl Acad Sci USA www.pnas.org/cgi/doi/10.1073/pnas.1300018110.
141. Davidson DJ, Andrews J (2013) Not all about consumption. Science 339, 1286–1287.
142. Murphy DJ, Hall CAS (2011) Energy return on investment, peak oil, and the end of economic growth. Ann New York Acad Sci 1219, 52–72.
143. Palmer MA, Bernhardt ES, Schlesinger WH, Eshleman KN, Foufoula-Georgiou E, et al. (2010) Mountaintop mining consequences. Science 327, 148–149.
144. Allan JD (2004) Landscapes and riverscapes: The influence of land use on stream ecosystems. Annu Rev Eco Evol Syst 35, 257–284.
145. McCormick BC, Eshleman KN, Griffith JL, Townsend PA (2009) Detection of flooding responses at the river basin scale enhanced by land use change. Water Resoures Res 45, W08401.
146. Pond GJ, Passmore ME, Borsuk FA, Reynolds L, Rose CJ (2008) Downstream effects of mountaintop coal mining: comparing biological conditions using family- and genus-level macroinvertebrate bioassessment tools. J N Am Benthol Soc 27, 717–737.
147. McAuley SD, Kozar MD (2006) Ground-water quality in unmined areas and near reclaimed surface coal mines in the northern and central Appalachian coal regions, Pennsylvania and West Virginia, http://pubs.usgs.gov/sir/2006/5059/pdf/sir2006-5059.pdf.
148. Negley TL, Eshleman KN (2006) Comparison of stormflow responses of surface-mined and forested watersheds in the Appalachian Mountains, USA. Hydro Process 20, 3467–3483.
149. Simmons JA, Currie WS, Eshleman KN, Kuers K, Monteleone S, et al. (2008) Forest to reclaimed mine use change leads to altered ecosystem structure and function. Ecolog Appl 18, 104–118.
150. Energy Resources and Conservation Board (2012) Alberta's energy reserves 2011 and supply/demand outlook – Appendix D, www.ercb.ca/sts/ST98/ST98-2012.pdf.
151. Jordaan SM, Keith DW, Stelfox B (2009) Quantifying land use of oil sands production: a life cycle perspective. Environ Res Lett 4, 1–15.
152. Yeh S, Jordaan SM, Brandt AR, Turetsky MR, Spatari S, et al. (2010) Land use greenhouse gas emissions from conventional oil production and oil sands. Environ Sci Technol 44, 8766–8772.
153. Charpentier AD, Bergerson JA, MacLean HL (2009) Understanding the Canadian oil snads industry's greenhouse gas emissions. Environ Res Lett 4, 014005, 11 pp.
154. Johnson EA, Miyanishi K (2008) Creating new landscapes and ecosystems: the Alberta oil sands. Ann NY Acad Sci 1134, 120–145.
155. Allen L, Cohen MJ, Abelson D, Miller B (2011) Fossil fuels and water quality, in The World's Water, Springer, 73–96.
156. Rooney RC, Bayley SE, Schindler DW (2011) Oil sands mining and reclamation cause massive loss of peatland and stored carbon. Proc Natl Acad Sci USA, www.pnas.org/cgi/doi/10.1073/pnas.1117693108.
157. Kurek J, Kirk JL, Muir DCG, Wang X, Evans MS, et al. (2013) Legacy of a half century of Athabasca oil sands development recorded by lake ecosystems. Proc Natl Acad Sci USA www.pnas.org/cgi/doi/10.1073/pnas.1217675110.
158. Kelly EN, Schindler DW, Hodson PV, Short JW, Radmanovich R, et al. (2010) Oil sands development contributes elements toxic at low concentrations to the Athabasca River and its tributaries. Proc Natl Acad Sci USA 107, 16178–16183.
159. Schmidt CW (2011) Blind Rush? Shale gas boom proceeds amid human health questions. Environ Health Perspec 119, A348–A353.
160. Kargbo DM, Wilhelm RG, Caampbell DJ (2010) Natural gas plays in the Marcellus shale: challenges and potential opportunities. Environ Sci Technol 44, 5679–5684.
161. Gregory KB, Vidic RD, Dzombak DA (2011) Water management challenges associated with the production of shale gas by hydraulic fracturing. Elements 7, 181–186.
162. Riverkeeper (2011) Fractured communities: case studies of the environmental impacts of industrial gas drilling. http://tinyurl.com/373rpp4.
163. Osborn SG, Vengosh A, Warner NR, Jackson RB (2011) Methane contamination of drinking water accompanying gas-well drilling and hydraulic fracturing. Proc Natl Acad Sci USA 108, 8172–8176.
164. O'Sullivan F, Paltsev S (2012) Shale gas production: potential versus actual greenhouse gas emissions. Environ Res Lett 7, 044030.
165. Allen L, Cohen MJ, Abelson D, Miller B (2011) Fossil fuels and water quality, in The World's Water, Springer, New York, 73–96.
166. Hansen J, Sato M, Ruedy R, Lacis A, Asamoah K, et al. (1997) Forcings and chaos in interannual to decadal climate change. J Geophys Res 102, 25679–25720.
167. Hansen J, Sato M (2004) Greenhouse gas growth rates. Proc Natl Acad Sci USA 101: 16109–16114.
168. Archer D (2007) Methane hydrate stability and anthropogenic climate change. Biogeosciences 4: 521–544.
169. Joos F, Bruno M, Fink R, Siegenthaler U, Stocker TF, et al. (1996) An efficient and accurate representation of complex oceanic and biospheric models of anthropogenic carbon uptake. Tellus B Chem Phys Meterol 48: 397–417.
170. Kharecha PA, Hansen JE (2008) Implications of "peak oil" for atmospheric CO_2 and climate. Global Biogeochem Cy 22: GB3012.

Exhibit 2 to Declaration of Dr. James E. Hansen

Exhibit A 65

171. Stocker TF (2013) The closing door of climate targets. Science 339, 280–282.
172. Stocker BD, Strassmann K, Joos F (2011) Sensitivity of Holocene atmospheric CO_2 and the modern carbon budget to early human land use: analyses with a process-based model. Biogeosciences 8: 69–88.
173. Sarmiento JL, Gloor M, Gruber N, Beaulieu C, Jacobson AR, et al. (2010) Trends and regional distributions of land and ocean carbon sinks. Biogeosci 7, 2351–2367.
174. Hillel D, Rosenzweig C, editors (2011) Handbook of Climate Change and Agroecosystems: Impacts, Adaptation and Mitigation. London: Imperial College Press.
175. Lamb D (2011) Regreening the Bare Hills. New York: Springer. 547 p.
176. Smith P (2012) Agricultural greenhouse gas mitigation potential globally, in Europe and in the UK: what have we learned in the last 20 years? Global Change Biol 18: 35–43.
177. Rockstrom J, Falkenmark M, Karlberg L, Hoff H, Rost S, Gerten D (2009) Future water availaility for global food production: The potential of greenwater for increasing resilience to global change. Water Resour Res 45, W00A12, doi:10.1029/2007WR006767.
178. Smith P, Gregory PJ, van Vuuren D, Obersteiner M, Havlik P, et al. (2010) Competition for land. Philos T R Soc B 365: 2941–2957.
179. Malhi Y (2010) The carbon balance of tropical forest regions, 1990–2005. Curr Op Environ Sustain 2, 237–244.
180. Bala G, Caldeira K, Wickett M, Phillips TJ, Lobell DB, et al. (2007) Combined climate and carbon-cycle effects of large-scale deforestation. Proc Natl Acad Sci USA 104: 6550–6555.
181. Bonan GB (2008) Forests and climate change: Forcings, feedbacks, and the climate benefits of forests. Science 320: 1444–1449.
182. Zomer RJ, Trabucco A, Bossio DA, Verchot LV (2008) Climate change mitigation: A spatial analysis of global land suitability for clean development mechanism afforestation and reforestation. Agriculture Ecosystems & Environment 126: 67–80.
183. Tilman D, Hill J, Lehman C (2006) Carbon-negative biofuels from low-input high-diversity grassland biomass. Science 314: 1598–1600.
184. Fargione J, Hill J, Tilman D, Polasky S,Hawthorne P (2008) Land clearing and the biofuel carbon debt. Science 319: 1235–1238.
185. Searchinger T, Heimlich R, Houghton RA, Dong F, Elobeid A, et al. (2008) Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. Science 319: 1238–1240.
186. Stehfest E, Bouwman L, van Vuuren DP, den Elzen MGJ, Eickhout B, et al. (2009) Climate benefits of changing diet. Clim Chg 95: 83–102.
187. Hansen J, Kharecha P, Sato M (2013) Climate forcing growth rates: doubling down on our Faustian bargain. Envir Res Lett 8,011006, doi:10.1088/1748–9326/8/1/011006.
188. Earth System Research Laboratory (2013) www.esrl.noaa.gov/gmd/ccgg/trends/.
189. Frohlich C, Lean J (1998) The Sun's total irradiance: cycles and trends in the past two decades and associated climate change uncertainties. Geophys Res Lett 25, 4377–4380.
190. Hansen J, Sato M, Ruedy R, Kharecha P, Lacis A, et al. (2007) Dangerous human-made interference with climate: a GISS modelE study. Atmos Chem Phys 7, 2287–2312.
191. http://www.columbia.edu7mhs119/Solar/and original sources given therein.
192. Eddy JA (1776) The Maunder Minimum. Science 192, 1189–1202.
193. Lean J, Beer J, Bradley R (1995) Reconstruction of solar irradiance since 1610: implications for climate change. Geophys Res Lett 22: 3195–3198.
194. Jones GS, Lockwood M, Stott PA (2012) What influence will future solar activity changes over the 21st century have on projected global near-surface temperature changes? J Geophys Res 117: D05103.
195. Lu Z, Zhang Q, Streets DG (2011) Sulfur dioxide and primary carbonaceous aerosol emissions in China and India, 1996–2010. Atmos Chem Phys 11: 9839–9864.
196. Robock A (2000) Volcanic eruptions and climate. Rev Geophys 38: 191–219.
197. Gleckler PJ, Wigley TML, Santer BD, Gregory JM, AchutaRao K, et al. (2006) Krakatoa's signature persists in the ocean. Nature 439: 675.
198. Solomon S, Daniel JS, Sanford TJ, Murphy DM, Plattner GK, et al. (2010) Persistence of climate changes due to a range of greenhouse gases. Proc Natl Acad Sci USA 107: 18354–18359.
199. Broecker WS, Bond G, Klas M, Bonani G, Wolfi W (1990) A salt oscillator in the glacial North Atlantic? Paleoceanography 5, 469–477.
200. Hansen JE, Sato M (2012) Paleoclimate implications for human-made climate change, in *Climate Change: Inferences from Paleoclimate and Regional Aspects*. A. Berger, F. Mesinger, and D. Šijački, Eds. Springer, 21–48, doi:10.1007/978-3-7091-0973-1-2.
201. Eby M, Zickfeld K, Montenegro A, Archer D, Meissner KJ, et al. (2009) Lifetime of anthropogenic climate change: millennial time-scales of potential CO_2 and surface temperature perturbations. J Clim 22, 2501–2511.
202. DeAngelis H, Skvarca P (2003) Glacier surge after ice shelf collapse. Science 299, 1560–1562.
203. Pritchard HD, Ligtenberg SRM, Fricker HA, Vaughan DG, van den Broeke, et al. (2012) Antarctic ice-sheet loss driven by basal melting of ice shelves. Nature 484, 502–505.
204. Broecker WS, Peng TH (1982) Tracers in the Sea, Eldigio, Palisades, New York, 1982.
205. Kennett JP, Stott LD (1991) Abrupt deep-sea warming, paleoceanographic changes and benthic extinctions at the end of the Paleocene. Nature 353, 225–229.
206. Ridgwell A (2007) Interpreting transient carbonate compensation depth changes by marine sediment core modeling. Paleoceanography 22, PA4102.
207. Zeebe RE, Zachos JC, Dickens GR (2009) Carbon dioxide forcing alone insufficient to explain Palaeocene-Eocene Thermal Maximum warming. Nature Geosci 2, 576–580.
208. Berner RA (2004) The Phanerozoic Carbon Cycle: CO_2 and O_2, Oxford Univ. Press, New York.
209. Max MD (2003) Natural Gas Hydrate in Oceanic and Permafrost Environments. Boston: Kluwer Academic Publishers.
210. Kvenvolden KA (1993) Gas Hydrates - Geological Perspective and Global Change. Rev Geophys 31: 173–187.
211. Dickens GR, O'Neil JR, Rea DK, Owen RM (1995) Dissociation of oceanic methane hydrate as a cause of the carbon isotope excursion at the end of the Paleocene. Paleoceanography 10, 965–971.
212. DeConto RM, Galeotti S, Pagani M, Tracy D, Schaefer K, et al. (2012) Past extreme wrming events linked to massive carbon release from thawing permafrost. Nature 484, 87–91.
213. Walter K, Zimov S, Chanton J, Verbyla D, Chapin F (2006) Methane bubbling from Siberian thaw lakes as a positive feedback to climate warming. Nature 443: 71–75.
214. Shakhova N, Semiletov I, Salyuk A, Yusupov V, Kosmac D, et al. (2010) Extensive Methane Venting to the Atmosphere from Sediments of the East Siberian Arctic Shelf. Science 327: 1246–1250.
215. O'Connor FM, Boucher O, Gedney N, Jones CD, Folberth GA, et al. (2010) Possible role of wetlands, permafrost, and methane hydrates in the methane cycle under future climate change: a review. Rev Geophys 48, RG4005.
216. Lunt DJ, Haywood AM, Schmidt GA, Salzmann U, Valdes PJ et al. (2010) Earth system sensitivity inferred from Pliocene modelling and data. Nature Geosci 3: 60–64.
217. Harris NL, Brown S, Hagen SC, Saatchi SS, Petrova S, et al. (2012) Baseline map of carbon emissions from deforestation in tropical regions. Science 336, 1573–1576.
218. Matthews HD, Keith DW (2007) Carbon-cycle feedbacks increase the likelihood of a warmer future. Geophys Res Lett 34: L09702.
219. Friedlingstein P, Cox P, Betts R, Bopp L, von Bloh W, et al. (2006) Climate-Carbon Cycle feedback analysis: results fromC4MIP model intercomparison. J Clim 19, 3337–3353.
220. Huntingford C, Zelazowski P, Galbraith D, Mercado LM, Sitch S, et al. (2013) Simulated resilience of tropical rainforests to CO_2-induced climate change. Nature Geosciece, doi:10.1038/ngeo1741.
221. Naik V, Mauzerall D, Horowitz L, Schwarzkopf MD, Ramaswamy V, et al. (2005) Net radiative forcing due to changes in regional emissions of tropospheric ozone precursors. J Geophys Res 110, D24, doi:10.1029/2005JD005908.
222. Beerling DJ, Stevenson DS, Valdes PJ (2011) Enhanced chemistry-climate feedbacks in past greenhouse worlds. Proc Natl Acad Sci USA 108, 9770–9775.
223. Shepherd J (2009) Geoengineering the climate: science, governance and uncertainty. London: The Royal Society, London, 84 pp. available http://www.royalsociety.org.
224. Budyko MI (1977) Climate changes. American Geophysical Union, Washington, DC, p. 244.
225. Robock A (2008) 20 reasons why geoengineering may be a bad idea. Bull Atom Sci 64, 14–18.
226. Keith DW, Ha-Duong M, Stolaroff JK (2006) Climate strategy with CO_2 capture from the air. Clim. Chg 74: 17–45.
227. House KZ, Baclig AC, Ranjan M, van Nierop EA, Wilcox J, et al. (2011) Economic and energetic analysis of capturing CO_2 from ambient air. Proc Natl Acad Sci USA 108, 20428–20433.
228. APS (2011) Direct Air Capture of CO_2 with Chemicals: A Technology Assessment for the APS Panel on Public Affairs. American Physical Society. Available: http://www.aps.org/policy/reports/assessments/upload/dac2011.pdf. Accessed Jan 11, 2012.
229. U.S. Energy Information Administration (2012) Annual Energy Review 2011, 370 pp., www.eia.gov/aer.
230. Pauwelyn J (2012) Carbon leakage measures and border tax adjustments under WTO law, in Research Handbook on Environment, Health and the WTO 48–49, eds. Provost Cand Van Calster G.
231. International Energy Agency (2012), "World energy balances", *IEA World Energy Statistics and Balances* (database). doi: 10.1787/data-00512-en. Accessed Mar. 2013.
232. Kharecha P, Hansen J (2013) Prevented mortality and greenhouse gas emissions from historical and projected nuclear power. Envir Sci Tech 47: 4889–4895.
233. International Energy Agency (2012), *World Energy Outlook 2012*. 690pp. OECD/IEA (http://www.worldenergyoutlook.org/publications/weo-2012/).
234. Cohen AJ, Ross Anderson H, Ostro B, Pandey KD, Krzyzanowski M, et al. (2005) The Global Burden of Disease Due to Outdoor Air Pollution. J Toxicol Environ Health A 68: 1301–1307.
235. Ackerman F, Stanton EA (2012) Climate Risks and Carbon Prices: Revising the Social Cost of Carbon. Economics E-journal 6, 2012–10.5018/economics-ejournal.ja.2012–10.

Exhibit 2 to Declaration of Dr. James E. Hansen

Exhibit A 66

236. Hsu S-L (2011) The Case for a Carbon Tax. Washington, DC: Island Press.
237. Hansen J (2009) Storms of My Grandchildren. New York: Bloomsbury. 304 pp.
238. Lochhead C (2013) George Shultz pushes for carbon tax. San Francisco Chronicle, 8 March.
239. Stern N (2007) Stern Review on the Economics of Climate Change Cambridge: Cambridge University Press.
240. Ackerman F, DeCanio S, Howarth R, Sheeran K (2009) Limitations of integrated assessment models of climate change. Clim Change 95: 297–315.
241. Komanoff C (2011) 5-Sector Carbon Tax Model: http://www.komanoff.net/fossil/CTC_Carbon_Tax_Model.xls. Accessed December 25, 2011.
242. United States Department of State (2011) Final Environmental Impact Statement. Available: http://www.state.gov/r/pa/prs/ps/2011/08/171084.htm. Accessed 09 February 2013.
243. Till CE, Chang YI (2011) Plentiful energy: the story of the integral fast reactor United States: Charles E. Till and Yoon Il Chang. 116 pp.
244. Kramer D (2012) Scientists poke holes in carbon dioxide sequestration. Phys Today 65: 22–24.
245. Tollefson J (2012) Air sampling reveals high emissions from gas fields. Nature 482, 139–140.
246. Tollefson J (2013) Methane leaks erode green credentials of natural gas. Nature 493, 12.
247. Petron G, Frost GJ, Miller BR, Hirsch AL, Montzka SA, et al. (2012) Hydrocarbon emissions characterizations in the Colorado Front Range. J Geophys Res 117, D04304.
248. Petron G, Frost GJ, Trainer MK, Miller BR, Dlugokencky EJ, et al. (2013) Reply to comment on "Hydrocarbon emissions characterization in the Colirado Front Range – A pilot study" by Michael A. Levi. J Geophys Res 118, D018487.
249. Alvarez RA, Pacala SW, Winebrake JJ, Chameides WL, Hamburg SP (2012) Greater focus needed on methane leakage from natural gas infrastructure. Proc Natl Acad Sci USA.
250. Oreskes N, Conway EM (2010) Merchants of Doubt: How a Handful of Scientists Obscured the Truth on Issues from Tobacco Smoke to Global Warming. New York: Bloomsbury Press. 355 pp. merchantsofdoubt.org.
251. Wood MC (2009) Atmospheric Trust Litigation. In: Burns WCG, Osofsky HM, editors. Adjudicating Climate Change: Sub-National, National, And Supra-National Approaches. Cambridge: Cambridge University Press. 99–125. Available: http://www.law.uoregon.edu/faculty/mwood/docs/atmospheric.pdf.
252. Alec L v. Jackson DDC, No. 11-CV-02235, 12/14/11 (United States District Court, District of Columbia).
253. Universal Declaration of Human Rights (http://www.un.org/en/documents/udhr/).
254. Meinshausen M, Meinshausen N, Hare W, Raper SCB, Frieler K, et al. (2009) Greenhouse gas emission targets for limiting global warming to 2°C. Nature 458, 1158–1162.
255. McKibben B (2012) Global warming's terrifying new math. Rolling Stone, August 2.
256. Houghton RA (2003) Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850–2000. Tellus B 55: 378–390.
257. http://unfccc.int/kyoto_protocol/items/2830.php.
258. http://www.regjeringen.no/en/dep/md/documents-and-publications/government-propositions-and-reports-/reports-to-the-storting-white-papers-2/2011-2012/report-no-21-2011-2012.html?id=707321.
259. http://www.statoil.com/en/NewsAndMedia/News/EnergyPerspectives/Pages/default.aspx.

Atmos. Chem. Phys. Discuss., 15, 20059–20179, 2015
www.atmos-chem-phys-discuss.net/15/20059/2015/
doi:10.5194/acpd-15-20059-2015

Atmospheric Chemistry and Physics
Discussions
Open Access

Ice melt, sea level rise and superstorms: evidence from paleoclimate data, climate modeling, and modern observations that 2 °C global warming is highly dangerous

J. Hansen[1], M. Sato[1], P. Hearty[2], R. Ruedy[3,4], M. Kelley[3,4], V. Masson-Delmotte[5], G. Russell[4], G. Tselioudis[4], J. Cao[6], E. Rignot[7,8], I. Velicogna[8,7], E. Kandiano[9], K. von Schuckmann[10], P. Kharecha[1,4], A. N. Legrande[4], M. Bauer[11], and K.-W. Lo[3,4]

[1]Climate Science, Awareness and Solutions, Columbia University Earth Institute, New York, NY 10115, USA
[2]Department of Environmental Studies, University of North Carolina at Wilmington, North Carolina 28403, USA
[3]Trinnovium LLC, New York, NY 10025, USA
[4]NASA Goddard Institute for Space Studies, 2880 Broadway, New York, NY 10025, USA
[5]Institut Pierre Simon Laplace, Laboratoire des Sciences du Climat et de l'Environnement (CEA-CNRS-UVSQ), Gif-sur-Yvette, France

[6]Key Lab of Aerosol Chemistry & Physics, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an 710075, China
[7]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, 91109, USA
[8]Department of Earth System Science, University of California, Irvine, California, 92697, USA
[9]GEOMAR, Helmholtz Centre for Ocean Research, Wischhofstrasse 1–3, Kiel 24148, Germany
[10]Mediterranean Institute of Oceanography, University of Toulon, La Garde, France
[11]Department of Applied Physics and Applied Mathematics, Columbia University, New York, NY, 10027, USA

Received: 11 June 2015 – Accepted: 9 July 2015 – Published: 23 July 2015

Correspondence to: J. Hansen (jeh1@columbia.edu)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

Abstract

There is evidence of ice melt, sea level rise to +5–9 m, and extreme storms in the prior interglacial period that was less than 1 °C warmer than today. Human-made climate forcing is stronger and more rapid than paleo forcings, but much can be learned by combining insights from paleoclimate, climate modeling, and on-going observations. We argue that ice sheets in contact with the ocean are vulnerable to non-linear disintegration in response to ocean warming, and we posit that ice sheet mass loss can be approximated by a doubling time up to sea level rise of at least several meters. Doubling times of 10, 20 or 40 years yield sea level rise of several meters in 50, 100 or 200 years. Paleoclimate data reveal that subsurface ocean warming causes ice shelf melt and ice sheet discharge. Our climate model exposes amplifying feedbacks in the Southern Ocean that slow Antarctic bottom water formation and increase ocean temperature near ice shelf grounding lines, while cooling the surface ocean and increasing sea ice cover and water column stability. Ocean surface cooling, in the North Atlantic as well as the Southern Ocean, increases tropospheric horizontal temperature gradients, eddy kinetic energy and baroclinicity, which drive more powerful storms. We focus attention on the Southern Ocean's role in affecting atmospheric CO_2 amount, which in turn is a tight control knob on global climate. The millennial (500–2000 year) time scale of deep ocean ventilation affects the time scale for natural CO_2 change, thus the time scale for paleo global climate, ice sheet and sea level changes. This millennial carbon cycle time scale should not be misinterpreted as the ice sheet time scale for response to a rapid human-made climate forcing. Recent ice sheet melt rates have a doubling time near the lower end of the 10–40 year range. We conclude that 2 °C global warming above the preindustrial level, which would spur more ice shelf melt, is highly dangerous. Earth's energy imbalance, which must be eliminated to stabilize climate, provides a crucial metric.

1 Introduction

Humanity is rapidly extracting and burning fossil fuels without full understanding of the consequences. Current assessments place emphasis on practical effects such as increasing extremes of heat waves, droughts, heavy rainfall, floods, and encroaching seas (IPCC, 2014; USNCA, 2014). These assessments and our recent study (Hansen et al., 2013a) conclude that there is an urgency to slow carbon dioxide (CO_2) emissions, because the longevity of the carbon in the climate system (Archer, 2005) and persistence of the induced warming (Solomon et al., 2010) may lock in unavoidable highly undesirable consequences.

Despite these warnings, global CO_2 emissions continue to increase as fossil fuels remain the primary energy source. The argument is made that it is economically and morally responsible to continue fossil fuel use for the sake of raising living standards, with expectation that humanity can adapt to climate change and find ways to minimize effects via advanced technologies.

We suggest that this viewpoint fails to appreciate the nature of the threat posed by ice sheet instability and sea level rise. If the ocean continues to accumulate heat and increase melting of marine-terminating ice shelves of Antarctica and Greenland, a point will be reached at which it is impossible to avoid large scale ice sheet disintegration with sea level rise of at least several meters. The economic and social cost of losing functionality of all coastal cities is practically incalculable. We suggest that a strategic approach relying on adaptation to such consequences is unacceptable to most of humanity, so it is important to understand this threat as soon as possible.

We examine events late in the last interglacial period warmer than today, called Marine Isotope Stage (MIS) 5e in studies of ocean sediment cores, Eemian in European climate studies, and sometimes Sangamonian in American literature (see Sect. 5 for timescale diagram of Marine Isotope Stages). Accurately known changes of Earth's astronomical configuration altered the seasonal and geographical distribution of incoming radiation during the Eemian. Resulting global warming was due to feedbacks that am-

plified the orbital forcing. While the Eemian is not an analog of future warming, it is useful for investigating climate feedbacks, the response of polar ice sheets to polar warming, and the interplay between ocean circulation and ice sheet melt.

Our study relies on a large body of research by the scientific community. After introducing evidence concerning late Eemian climate change, we analyze relevant climate processes in three stages. First we carry our IPCC-like climate simulations, but with growing freshwater sources in the North Atlantic and Southern Oceans. Second we use paleoclimate data to extract information on key processes identified by the modeling. Third we use modern data to show that these processes are already spurring climate change today.

2 Evidence concerning Eemian climate

We first discuss geologic evidence of late-Eemian sea level rise and storms. We then discuss ocean core data that help define a rapid cooling event in the North Atlantic that marks the initial descent from interglacial conditions toward global ice age conditions. This rapid end-Eemian cooling occurs at ~118 ky b2k in ocean cores with uncertainty ~2 ky, and is identified by Chapman and Shackleton (1999) as cold event C26.

C26 is the cold phase of Dansgaard–Oeschger climate oscillation D–O 26 in the NGRIP (North Greenland Ice Core Project) ice core (NGRIP, 2004). C26 begins with a sharp cooling at 119.14 ky b2k on the GICC05modelext time scale (Rasmussen et al., 2014). The GICC05 time scale is based on annual layer counting in Greenland ice cores for the last 60 ky and on an ice flow-model extension for earlier times. An alternative time scale is provided by Antarctic ice core chronology AICC2012 (Bazin et al., 2013; Veres et al., 2013) on which Greenland ice core records have been synchronized via global markers such as oscillations of atmospheric CH_4 amount. C26 on Greenland is at 116.72 ky b2k on the AICC2012 time scale. Figure S1 in the Supplement shows the difference between GICC05 and AICC2012 times scales versus time.

This age uncertainty for C26 is consistent with the ice core 2σ error estimate of 3.2 ky at Eemian time (Bazin et al., 2013). Despite this absolute age uncertainty, we can use Greenland data synchronized to the AICC2012 time scale to determine the relative timing of Greenland and Antarctic climate changes (Sect. 5) to an accuracy of a few decades (Bazin et al., 2013).

2.1 Eemian sea level

Eemian sea level is of special interest because Eemian climate was at most ~2 °C warmer than pre-industrial climate, thus at most ~1 °C warmer than today. Indeed, based on multiple data and model sources Masson-Delmotte et al. (2013) suggest that peak Eemian temperature was only a few tenths of a degree warmer than today. The Eemian period thus provides an indication of sea level change that can be expected if global temperature reaches and maintains a level moderately higher than today. Eemian sea level reached heights several meters above today's level (Chen et al., 1991; Neumann and Hearty, 1996; Hearty et al., 2007; Kopp et al., 2009; Dutton and Lambeck, 2012; O'Leary et al., 2013). Although climate forcings were weak and changed slowly during the Eemian, there were probably instances in the Eemian with sea level change of the order of 1 m century^{-1} (Rohling et al., 2008; W. Thompson et al., 2011; Blanchon et al., 2009).

Hearty et al. (2007) used shoreline stratigraphy, field information, and geochronological data from 15 sites around the world to construct a composite curve of Eemian sea level change. Their reconstruction has sea level rising in the early Eemian to +2–3 m ("+" indicates above today's sea level). Mid-Eemian sea level may have fallen a few meters to a level near today's sea level. Sea level rose rapidly in the late Eemian when it cut multiple bioerosional notches in older limestone in the Bahamas and elsewhere at +6–9 m. These brief upward shifts of sea level were interpreted as evidence of rapid ice melt events.

This sea level behavior may be surprising at first glance, and it is easy to question specific details because of the difficulties in sea level reconstructions, including the

Exhibit 3 to Declaration of Dr. James E. Hansen

Exhibit A 70

effect of regional glacio-isostatic adjustment (GIA) of Earth's crust as ice sheets grow and decay. Indeed, rapid late-Eemian sea level rise is unexpected, because seasonal insolation anomalies favored growth of Northern Hemisphere ice at that time. However, the basic conclusion that arises from global studies is a sea level elevation difference of 3–5 m between late and early Eemian. We will show in the remainder of this paper that there is now substantial supporting evidence for these sea level change features and a rational interpretation.

Assessed chronology of sea level change depends on ages estimated for fossil corals. The analytic uncertainty of uranium radioactive decay (U-series) ages is about 1 ky (Edwards et al., 2003; Scholz and Mangini, 2007), but often undetectable diagenetic effects can increase the error (Bard et al., 1992; Thompson and Goldstein, 2005). The growth position of corals is a good, though not comprehensive, indicator of sea level, because sea level had to be higher than the reef at the time of coral growth. However, some corals grow at a range of depths, which adds uncertainty. Furthermore, if sea level rises too fast, corals tend to "give up" or founder, only recording minimum sea level (Neumann and MacIntyre, 1985), and if sea level falls corals are exposed, die, and thus stop recording sea level. Mobile carbonate sediments that mantle limestone platforms such as Bermuda and the Bahamas record rapid sea level change effectively, because the sediments respond and cement quickly, thus preserving sea level change evidence.

Hearty and Kindler (1993), White et al. (1998) and Wilson et al. (1998) describe evidence in fossil Bahamian reefs of a mid-Eemian regressive-transgressive cycle (sea level fall and rise). They estimated a sea level fall from +4 m to approximately today's level, and then a rise to at least +6 m. U-series dating defined the period of fall and rise as a maximum of 1500 years covering ~ 125 to 124 ky b2k, and the high stand lasting until ~ 119 ky b2k. Such rapid sea level change requires ice sheet growth and melt, regional lithospheric adjustment, or both.

Blanchon et al. (2009) used a sequence of coral reef crests from northeast Yucatan peninsula, Mexico, to investigate sea level change with a higher temporal precision

than possible with U-series dating alone. They used coral reef "back-stepping", i.e., the fact that the location of coral reef building moves shoreward as sea level rises, to infer sea level change. They found that in the latter half of the Eemian there was a point at which sea level jumped by 2–3 m within an "ecological" period, i.e., within several decades. From U-series dating they estimated that this period of rapid sea level rise occurred at about 121 ky b2k. W. Thompson et al. (2011) reexamined Eemian coral reef data from the Bahamas with a method that corrected uranium-thorium ages for diagenic disturbances. They confirmed a mid-Eemian sea level minimum, putting sea level at +4 m at 123 ky b2k, at +6 m at 119 ky b2k, and at 0 m at some time in between, again noting that coral reefs only record minimum sea level.

Despite general consistency among these studies, considerable uncertainty remains about details of Eemian sea level change. Sources of uncertainty include post-depositional effects of GIA and local tectonics. Global models of GIA of Earth's crust to loading and unloading of ice sheets are used increasingly to improve assessments of past sea level change. Although GIA models contain uncertain parameters, they provide a useful indication of possible displacement of geological sea level indicators. O'Leary et al. (2013) provide a new perspective on Eemian sea level change using over 100 well-dated U-series coral reefs at 28 sites along the 1400 km west coast of Australia and incorporating GIA corrections on regional sea level. In agreement with Hearty et al. (2007), their analyses suggest that sea level was relatively stable at 3–4 m in most of the Eemian, followed by a rapid (< 1000 yr) late-Eemian sea level rise to about +9 m. U-series dating of the corals has the sea level rise begin at 119 ky b2k and peak sea level at 118.1 ± 1.4 ky b2k. This dating of peak sea level is consistent with the estimate of Hearty and Neumann (2001) of ~ 118 ky b2k as the time of rapid climate changes and extreme storminess.

End-Eemian sea level rise would seem to be a paradox, because orbital forcing then favored growth of Northern Hemisphere ice sheets. We will find evidence, however, that the sea level rise and increased storminess are consistent, and likely related to events in the Southern Ocean.

2.2 Evidence of end-Eemian storms in Bahamas and Bermuda

Late-Eemian sea level rise was followed by rapid sea level fall at the end of MIS 5e (Neumann and Hearty, 1996; Stirling et al., 1998; McCulloch and Esat, 2000; Lambeck and Chappell, 2001; Lea et al., 2002). Geologic data suggest that this sea level oscillation was accompanied by increased temperature gradients and storminess in the North Atlantic region. Here we summarize evidence for end-Eemian storminess, based mainly on geological studies of Neumann and Hearty (1996), Hearty (1997), Hearty et al. (1998), Hearty and Neumann (2001) and Hearty et al. (2007) in Bermuda and the Bahamas. In following sections we examine data from ocean sediment cores relevant to climate events in this period and then make global climate simulations, which help us suggest causal connections among end-Eemian events.

The Bahama Banks are low-lying carbonate platforms that are exposed during glacials and largely flooded during interglacial high stands. From a tectonic perspective, the platforms are relatively stable, but may have experienced minor GIA effects. When flooded during MIS 5e sea level rise, enormous volumes of aragonitic oolitic grains were generated across the shallow high energy banks, shoals, ridges, and dunes, where storm deposits indurated rapidly upon subaerial exposure, preserving rock evidence of brief, high-energy events. The preserved stratigraphic, sedimentary and geomorphic features attest to the energy of the late-Eemian Atlantic Ocean and point to a turbulent end-Eemian transition.

In the Bahama Islands, extensive oolitic sand ridges with a distinctive landward-pointing V-shape are common, each standing in relief across several kilometers of low area (Hearty et al., 1998). Termed “chevron ridges” from their characteristic V-shape, these beach ridges are found on broad, low lying platforms or ramps throughout the Atlantic-facing, deep-water margins of the Bahamas. Hearty et al. (1998) examined 35 areas with chevron ridges across the Bahamas, which all point in a southwest direction (S65° W) with no apparent relation to the variable configuration of the coastline.

The lightly indurated ooid sand ridges are several kilometers long and appear to have originated from the action of long-period waves from a northeasterly Atlantic source. The chevron ridges contain bands of beach fenestrae, formed by air bubbles trapped in fine ooid sand inundated by water and quickly indurated. The internal sedimentary structures including the beach fenestrae and scour structures (Tormey, 2015) show that the chevrons were rapidly emplaced by water rather than wind (Hearty et al., 1998). These landforms were deposited near the end of a sea level high stand, when sea level was just beginning to fall, otherwise they would have been reworked subsequently by stable or rising seas. Some chevrons contain multiple smaller ridges “nested” in a seaward direction (Hearty et al., 1998), providing further evidence that sea level was falling fast enough to strand and preserve older chevrons as distinct landforms.

Fine-grained carbonate ooids cement rapidly, sometimes within decades to a century, if left immobile (Taft et al., 1968; Curran et al., 2008). Additional evidence of the rapid emplacement of the sand ridges is inferred from burial of large trees and fronds in living positions (Neumann and Hearty, 1996; Hearty and Olson, 2011). Fenestrae are abundant primarily in the youngest 5e beds throughout the eastern margin of the Bahamas.

Older ridges adjacent to the chevron ridges have wave runup deposits that reach heights nearly 40 m above present sea level, far above the reach of a quiescent 5e sea surface. Such elevated beach fenestrae are considered to result from runup of very large waves (Wanless and Dravis, 1989). These stratigraphically youngest deposits on the shore-parallel ridges are 1-5 m thick fenestrae-filled seaward-sloping tabular beds of stage 5e age that mantle older MIS 5e dune deposits (Neumann and Moore, 1975; Chen at al., 1991; Neumann and Hearty, 1996; Tormey, 2015). Runup beds reach more than a kilometer from the present coast, mantling the eastern flanks of stage 5e ridges (Hearty et al., 1998). Bain and Kindler (1994) suggested the fenestrae could be rain-generated, but the fenestrae at high elevations are widespread and exclusive to the late 5e deposits. They are not commonly found in older dune ridges (Hearty et al., 1998).

Enormous boulders tossed onto an older Pleistocene landscape (Hearty, 1997; Hearty et al., 1998; Hearty and Neumann, 2001) provide a metric of powerful waves at the end of stage 5e. Giant displaced boulders (Fig. 1) were deposited in north Eleuthera, Bahamas near chevron ridges and runup deposits (Hearty, 1997). The boulders are composed of recrystallized oolitic-peloidal limestone of MIS 9 or 11 age (300–400 ky; Kindler and Hearty, 1996; Hearty, 1998). The boulders rest on oolitic sediments and fossils typical of MIS 5e, and thus were deposited after most of the interglacial had passed. The maximum age of boulder emplacement is ~115–120 ky based on their stratigraphy and association with regressive stage 5e marine, eolian and fossil land snail (*Cerion*) deposits (Hearty, 1997; Hearty et al., 1998). Hearty (1997) reasoned that the boulders were emplaced during the latest substage 5e highstand, while sea level remained high, because even larger waves would have been required at times of lower sea level during MIS sub-stages 5c and 5a in order to lift the boulders over the cliffs.

The boulders must have been transported to their present position by waves, as two of the largest ones (Fig. 1) are located on the crest of the island's ridge, eliminating the possibility that they were moved downward by gravity (Hearty, 1998) or are the karstic remnants of some ancient landscape. A tsunami conceivably deposited the boulders, but the area is not near a tectonic plate boundary. The coincidence of a tsunami at the end-Eemian moment is improbable given the absence of evidence of tsunamis at other times in the Bahamas and the lack of evidence of tsunamis on the Atlantic Coastal Plain of the United States. The proximity of run-up deposits and nested chevron ridges across a broad front of Bahamian islands is clear evidence of a sustained series of high-energy wave events.

The remarkable size of the boulders in north Eleuthera becomes more comprehensible upon realization that numerous boulders larger than 10 m^3 have been thrown up on Eleuthera Island by storms during the Holocene (Hearty, 1997). The mass and volume of the Holocene boulders (the largest ~90 m^3, Table 4 of Hearty, 1997) are about 10× smaller than the MIS 5e boulders (Table 2 of Hearty, 1997). Hearty (1998) notes that the

large 5e and Holocene boulders are all located at the apex of a narrowing horseshoe-shaped submerged embayment (Fig. 2 of Hearty, 1997). Long period ocean waves are funneled into this embayment, generating huge surge and splash even today as they impact the cliffs near the Glass Window Bridge.

Movement of these sediments, including chevrons, run-up deposits and boulders, required a potent sustained energy source. Anticipating our interpretation in terms of powerful storms driven by an unusually warm tropical ocean and strong zonal temperature gradients in the North Atlantic, we must ask whether there should not be evidence of comparable end-Eemian storms in Bermuda. Indeed, there are seaward sloping planar beds rising to about +20 m along several kilometers of the north coast of Bermuda (Land et al., 1967; Vacher and Rowe, 1997; Hearty et al., 1998). These beds, from the latest stage 5e, are filled with beach fenestrae in platy grains and thick air-filled laminations, in marked contrast to older stage 5 sedimentary structures that underlie them (Hearty et al., 1998). Meter-scale, subtidal cross beds comprise the seaward facies of the elevated beach beds, reflecting an interval of exceptional wave energy on the normally tranquil, shallow and broad north shore platform of Bermuda.

Given the geologic evidence of high seas and storminess from Bermuda and the Bahamas, Hearty and Neumann (2001) suggested "Steeper pressure, temperature, and moisture gradients adjacent to warm tropical waters could presumably spawn larger and more frequent cyclonic storms in the North Atlantic than those seen today." We now seek further evidence related to the question of whether powerful end-Eemian storms in the North Atlantic may have dispersed long-period, well-organized waves to the southwest.

2.3 End-Eemian evidence from North Atlantic sediment cores

Sediment cores from multiple locations provide information not only on ocean temperature and circulation changes (Fig. 2), but also changes on ice sheet destabilization inferred from ice rafted debris. Comparison of data from different sites is affected by inaccuracy in absolute dating and use of different age models. Dating of sediments is

usually based on tuning to the time scale of Earth orbital variations (Martinson et al., 1987) or "wiggle-matching" to another record (Sirocko et al., 2005), which limits accuracy to several ky. Temporal resolution is limited by bioturbation of sediments; thus resolution varies with core location and climate (Keigwin and Jones, 1994). For example, high deposition rates during ice ages at the Bermuda Rise yield a resolution of a few decades, but low sedimentation rates during the Eemian yield a resolution of a few centuries (Lehman et al., 2002). Lateral transport of sedimentary material prior to deposition complicates data interpretation and can introduce uncertainty, as argued specifically regarding data from the Bermuda Rise (Ohkouchi et al., 2002; Engelbrecht and Sachs, 2005).

Adkins et al. (1997) analyzed sediment core (MD95-2036, 34° N, 58° W) from the Bermuda Rise using an age model based on Martinson et al. (1987) orbital tuning with the MIS stage 5/6 transition set at 131 ky b2k and the stage 5d/5e transition at 114 ky b2k. They found that oxygen isotope $\delta^{18}O$ of planktonic (near-surface dwelling) foraminifera and benthic (deep ocean) foraminifera both attain full interglacial values at ~128 ky b2k and remain nearly constant for ~10 ky (their Fig. 2). Adkins et al. (1997) infer that: "Late within isotope stage 5e (~118 ky b2k), there is a rapid shift in oceanic conditions in the western North Atlantic..." They find in the sediments at that point an abrupt increase of clays indicative of enhanced land-based glacier melt and an increase of high nutrient "southern source waters". The latter change implies a shutdown or diminution of NADW formation that allows Antarctic Bottom Water (AABW) to push into the deep North Atlantic Ocean (Duplessy et al., 1988; Govin et al., 2009). Adkins et al. (1997) continue: "The rapid deep and surface hydrographic changes found in this core mark the end of the peak interglacial and the beginning of climate deterioration towards the semi-glacial stage 5d. Before and immediately after this event, signaling the impeding end of stage 5e, deep-water chemistry is similar to modern NADW." This last sentence refers to a temporary rebound to near interglacial conditions. In Sect. 5 we use accurately synchronized Greenland and Antarctic ice cores, which also reveal

this temporary end-Eemian climate rebound, to interpret the glacial inception and its relation to ice melt and late-Eemian sea level rise.

Ice rafted debris (IRD) found in ocean cores provides a useful climate diagnostic tool (Heinrich, 1988; Hemming, 2004). Massive ice rafting ("Heinrich") events are often associated with decreased NADW production and shutdown or slowdown of the Atlantic Meridional Overturning Circulation (AMOC) (Broecker, 2002; Barrieiro et al., 2008; Srokosz et al., 2012). However, ice rafting occurs on a continuum of scales, and significant IRD is found in the cold phase of all the 24 Dansgaard–Oeschger (D–O) climate oscillations first identified in Greenland ice cores (Dansgaard et al., 1993). D–O events exhibit rapid warming on Greenland of at least several degrees within a few decades or less, followed by cooling over a longer period. Chapman and Shackleton (1999) found IRD events in the NEAP18K core for all D–O events (C19–C24) within the core interval that they studied, and they also labeled two additional events (C25 and C26). C26 did not produce identifiable IRD at the NEAP18K site, but it was added to the series because of its strong surface cooling.

Lehman et al. (2002) quantify the C26 cooling event using the same Bermuda Rise core (MD95-2036) and age model as Adkins et al. (1997). Based on the alkenone paleo-temperature technique (Sachs and Lehman, 1999), Lehman et al. (2002) find a sharp sea surface temperature (SST) decrease of ~3 °C (their Fig. 1) at ~118 ky BP, coinciding with the end-Eemian shoulder of the benthic $\delta^{18}O$ plateau that defines stage 5e in the deep ocean. The SST partially recovered after several centuries, but C26 marked the start of a long slide into the depths of stage 5d cold, as ice sheets grew and sea level fell ~50 m in 10 ky (Lambeck and Chappell, 2001; Rohling et al., 2009). Lehman et al. (2002) wiggle-match the MD95-2036 and NEAP18K cores, finding a simple adjustment to the age model of Chapman and Shackleton (1999) that maximizes correlation of the benthic $\delta^{18}O$ records with the Adkins et al. (1997) $\delta^{18}O$ record. Specifically, they adjust the NEAP time scale by +4 ky before the MIS 5b $\delta^{18}O$ minimum and by +2 ky after it, which places C26 cooling at 118 ky b2k in both records.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

They give preference to the Adkins et al. (1997) age scale because it employs a ^{230}Th-based time scale between 100 and 130 ky b2k.

We do not assert that the end-Eemian C-26 cooling was necessarily at 118 ky b2k, but we suggest that the strong rapid cooling observed in several sediment cores in this region of the subtropical and midlatitude North Atlantic Drift at about this time were all probably the same event. Such a large cooling lasting for centuries would not likely be confined to a small region. The dating models in several other studies place the date of the end-Eemian shoulder of the deep ocean δ^{18}O and an accompanying surface cooling event in the range 116–118 ky b2k.

Kandiano et al. (2004) and Bauch and Kandiano (2007) analyze core M23414 (53° N, 17° W), west of Ireland, finding a major SST end-Eemian cooling that they identify as C26 and place at 117 ky b2k. The 1 ky change in the timing of this event compared with Lehman et al. (2002), is due to a minor change in the age model, specifically, Bauch and Kandiano say: "The original age model of MD95-2036 (Lehman et al., 2002) has been adjusted to our core M23414 by alignment of the 4 per mil level in the benthic δ^{18}O records (at 130 ka in M23414) and the prominent C24 event in both cores." Bauch and Erlenkeuser (2008) and H. Bauch et al. (2012) examine ocean cores along the North Atlantic Current including its continuation into the Nordic seas. They find that in the Greenland-Iceland-Norwegian (GIN) Sea, unlike middle latitudes, the Eemian was warmest near the end of the interglacial period. The age model employed by Bauch and Erlenkeuser (2008) has the Eemian about 2 ky younger than the Adkins et al. (1997) age model, Bauch and Erlenkeuser (2008) having the benthic δ^{18}O plateau at ~116–124 ky BP (their Fig. 6). Rapid cooling they illustrate there at ~116.6 ky BP for core M23071 on the Voring Plateau (67° N, 3° E) likely corresponds to the C26 end-Eemian cooling event.

Identification of end-Eemian cooling in ocean cores is hampered by the fact that Eemian North Atlantic climate was more variable than in the Holocene (Fronval and Jansen, 1996). There were at least three cooling events within the Eemian, each with minor increases in IRD, which are labeled C27, C27a and C27b by Oppo et al. (2006);

see their Fig. 2 for core site ODP-980 in the eastern North Atlantic (55° N, 15° W) near Ireland. High (sub-centennial) resolution cores in the Eirik drift region (MD03-2664, 57° N,49° W) near the southern tip of Greenland reveal an event with rapid cooling accompanied by reduction in NADW production (Irvali et al., 2012; Galaasen et al., 2014), which they place at ~117 ky b2k. However, their age scale has the benthic δ^{18}O shoulder at ~115 ky b2k (Fig. S1 in the Supplement, Galaasen et al., 2014), so that event may have been C27b with C26 being stronger cooling that occurred thereafter.

2.4 Eemian timing consistency with insolation anomalies

Glacial-interglacial climate cycles are affected by insolation change, as shown persuasively by Hays et al. (1976) and discussed in Sect. 5.1. Each "termination" (Broecker, 1984) of glacial conditions in the past several hundred thousand years coincided with a large positive warm-season insolation anomaly at the latitude of North American and Eurasian ice sheets (Raymo, 1997; Paillard, 2001). The explanation is that positive summer insolation anomalies (negative in winter) favor increased summer melting and reduced winter snowfall, thus shrinking ice sheets.

Termination timing is predicted better by high Northern Hemisphere late spring (April–May–June) insolation than by summer anomalies. For example, Raymo (1997) places Terminations I and II (preceding the Holocene and Eemian) midpoints at 13.5 and 128–131 ky b2k. Late spring insolation maxima are at 13.2 and 129.5 ky b2k (Fig. 4a). The AICC2012 ice core chronology (Bazin et al., 2013) places Termination II at 128.5 ky b2k, with 2σ uncertainty 3.2 ky. Late spring irradiance maximizes warm-season ice melt by producing the earliest feasible warm-season ice sheet darkening via snow melt and snow recrystallization (Hansen et al., 2007b).

Late Eemian sea level rise is seemingly a paradox, because glacial-interglacial sea level change is mainly a result of the growth and decay of Northern Hemisphere ice sheets. Northern warm-season insolation anomalies were negative and declining in the latter part of the Eemian (Fig. 3a), so Northern Hemisphere ice sheets should have been growing. We suggest that the explanation for a mid-Eemian sea level minimum is

a substantial late-Eemian collapse of the Antarctic ice sheet facilitated by the positive warm-season insolation anomaly on Antarctica and the Southern Ocean during the late Eemian (Fig. 3b).

Persuasive presentation of this interpretation requires analysis of relevant climate mechanisms with a global model as well as a detailed discussion of paleoclimate data. We will show that these analyses in turn help to explain ongoing climate change today, with implications for continuing climate change this century.

3 Simulations of 1850–2300 climate change

We make simulations for 1850–2300 with radiative forcings that were used for IPCC (2007, 2013) studies. This allows comparison with simulations made for prior studies.

3.1 Climate model

Simulations are made with an improved version of a coarse-resolution model that allows long runs at low cost, GISS (Goddard Institute for Space Studies) model E-R. The atmosphere model is the documented modelE (Schmidt et al., 2006). The ocean is based on the Russell et al. (1995) model that conserves water and salt mass, has a free surface with divergent flow, uses a linear upstream scheme for advection, allows flow through 12 sub-resolution straits, has background diffusivity $0.3\,\mathrm{cm^2\,s^{-1}}$, $4° \times 5°$ resolution and 13 layers that increase in thickness with depth.

However, the ocean model includes simple but significant changes, compared with the version documented in simulations by Miller et al. (2014). First, an error in the calculation of neutral surfaces in the Gent–McWilliams (GM, Gent and McWilliams, 1990) mesoscale eddy parameterization was corrected; the resulting increased slope of neutral surfaces provides proper leverage to the restratification process and correctly orients eddy stirring along those surfaces.

Second, the calculation of eddy diffusivity K_{meso} for GM following Visbeck et al. (1997) was simplified to use a length scale independent of the density structure (J. Marshall, personal communication, 2014):

$$K_{\mathrm{meso}} = C/[T_{\mathrm{eady}} \times f(\mathrm{latitude})] \tag{1}$$

where $C = (27.9\,\mathrm{km})^2$, Eady growth rate $1/T_{\mathrm{eady}} = \{|S \times N|\}$, S is the neutral surface slope, N the Brunt–Vaisala frequency, $\{\ \}$ signifies averaging over the upper D meters of ocean depth, $D =$ min(max(depth, 400 m), 1000 m), and f(latitude) = max(0.1, sin(| latitude |)) to qualitatively mimic the larger values of the Rossby radius of deformation at low latitudes. These choices for K_{meso}, whose simplicity is congruent with the use of a depth-independent eddy diffusivity and the use of $1/T_{\mathrm{eady}}$ as a metric of eddy energy, result in the zonal average diffusivity shown in Fig. 4.

Third, the so-called nonlocal terms in the KPP mixing parameterization (Large et al., 1994) were activated. All of these modifications tend to increase the ocean stratification, and in particular the Southern Ocean state is improved by the GM modifications. However, as is apparent in Fig. 4, drift in the Southern Ocean state leads to a modest reduction of the eddy diffusivities over the first 500 years of spin-up. Overall realism of the ocean circulation is improved, but significant model deficiencies remain, as we will describe.

The simulated Atlantic Meridional Overturning Circulation (AMOC) has maximum flux that varies within the range ∼ 14–18 Sv in the model control run (Figs. 5 and 6). AMOC strength in recent observations is 17.5 ± 1.6 Sv (Baringer et al., 2013; Srokosz et al., 2012), based on eight years (2004–2011) data for an in situ mooring array (Rayner et al., 2011; Johns et al., 2011).

Ocean model control run initial conditions are climatology for temperature and salinity (Levitus and Boyer, 1994; Levitus et al., 1994); atmospheric composition is that of 1880 (Hansen et al., 2011). Overall model drift from control run initial conditions is moderate (see Fig. S2 for planetary energy imbalance and global temperature), but there is drift in the North Atlantic circulation. The AMOC circulation cell initially is confined to the

upper 3 km at all latitudes (1st century in Figs. 5 and 6), but by the 5th century the cell reaches deeper at high latitudes.

Atmospheric and surface climate in the present model is similar to the documented modelE-R, but because of changes to the ocean model we provide several diagnostics in the Supplement. A notable flaw in the simulated surface climate is the unrealistic double precipitation maximum in the tropical Pacific (Fig. S3). This double ITCZ (intertropical convergence zone) occurs in many models and is related to the difficulty of producing realistic stratus clouds in the Eastern Tropical Pacific. Another flaw is unrealistic hemispheric sea ice, with too much sea ice in the Northern Hemisphere and too little in the Southern Hemisphere (Figs. S4 and S5). Excessive Northern Hemisphere sea ice might be caused by deficient poleward heat transport in the Atlantic Ocean (Fig. S6). However, the AMOC has realistic strength and Atlantic meridional heat transport is only slightly below observations at high latitudes (Fig. S6). Thus we suspect that the problem may lie in sea ice parameterizations or deficient dynamical transport of ice out of the Arctic. The deficient Southern Hemisphere sea ice, at least in part, is likely related to excessive poleward (southward) transport of heat by the simulated global ocean (Fig. S6), which is related to deficient northward transport of heat in the modeled Atlantic Ocean (Fig. S6).

A key characteristic of the model and the real world is the response time: how fast does the surface temperature adjust to a climate forcing, i.e., an imposed perturbation of the planet's energy balance? ModelE-R response is about 40 % in five years (Fig. 7) and 60 % in 100 years, with the remainder requiring many centuries. Hansen et al. (2011) concluded that most ocean models, including modelE-R, mix a surface temperature perturbation downward too efficiently and thus have a slower surface response than the real world. The basis for this conclusion was empirical analysis using climate response functions, with 50, 75 and 90 % response at year 100 for climate simulations (Hansen et al., 2011). Earth's measured energy imbalance in recent years and global temperature change in the past century revealed that the response function with

75 % response in 100 years provided a much better fit with observations than the other choices.

Durack et al. (2012) compared observations of how rapidly surface salinity changes are mixed into the deeper ocean with the large number of global models in the CMIP3 (Climate Model Intercomparison Project), reaching a similar conclusion, that the models mix too rapidly.

Our present ocean model has a faster response on 10–75 year time scales than the old model (Fig. 7), but the change is small. Although the climate response time in our model is comparable to that in many other ocean models (Hansen et al., 2011), we believe that it is likely slower than the response in the real world on time scales of a few decades and longer. A too slow surface response could result from excessive small scale mixing. We will suggest, after the studies below, that excessive mixing has other consequences, e.g., causing the effect of freshwater stratification on slowing AABW formation and growth of Antarctic sea ice cover to occur 1–2 decades later than in the real world. Similarly, excessive mixing may make the AMOC in the model less sensitive to freshwater forcing than the real world AMOC.

3.2 Experiment definition: exponentially increasing fresh water

Freshwater injection is specified as 360 Gt yr^{-1} (1 mm sea level) in 2003–2015, then growing with 5, 10 or 20 year doubling time (Fig. 8). Injection ends when input to global sea level reaches 1 or 5 m. The sharp cut-off aids separation of immediate forcing effects and feedbacks.

We do not argue for this specific input function, but we suggest that rapid meltwater increase is likely if GHGs continue to grow rapidly. Greenland and Antarctica have outlet glaciers occupying canyons with bedrock below sea level well back into the ice sheet (Fretwell et al., 2013; Morlighem et al., 2014; Pollard et al., 2015). Feedbacks, including ice sheet darkening due to surface melt (Hansen et al., 2007b; Robinson et al., 2012; Tedesco et al., 2013; Box et al., 2012) and lowering and thus warming of the near-coastal ice sheet surface, make increasing ice melt likely. Paleoclimate

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

data reveal instances of sea level rise of several meters in a century (Fairbanks, 1989; Deschamps et al., 2012). Those cases involved ice sheets at lower latitudes, but 21st century climate forcing is larger and increasing much more rapidly.

Radiative forcings are those of Hansen et al. (2007c), based on data through 2003 and IPCC scenario A1B for later GHGs. A1B is an intermediate IPCC scenario over the century, but on the high side early this century (Fig. 2, Hansen et al., 2007c). We add freshwater to the North Atlantic (ocean area within 52–72° N and 15° E–65° N) or Southern Ocean (ocean south of 60° S), or equally divided between the two oceans. Ice sheet discharge (icebergs plus meltwater) is mixed as fresh water with mean temperature −15 °C into top three ocean layers (Fig. S7).

3.3 Simulated surface temperature and energy balance

We present surface temperature and planetary energy balance first, thus providing a global overview. Then we examine changes in ocean circulation and compare results with prior studies.

Temperature change in 2065, 2080 and 2096 for 10 year doubling time (Fig. 9) should be thought of as results when sea level rise reaches 0.6, 1.7 and 5 m, because the dates depend on initial freshwater flux. Actual current freshwater flux may be about a factor of four higher than assumed in these initial runs, as we will discuss, and thus effects may occur ∼ 20 years earlier. A sea level rise of 5 m in a century is about the most extreme in the paleo record (Fairbanks, 1989; Deschamps et al., 2012), but the assumed 21st century climate forcing is also more rapidly growing than any known natural forcing.

Meltwater injected on the North Atlantic has larger initial impact, but Southern Hemisphere ice melt has a greater global effect for larger melt as the effectiveness of more meltwater in the North Atlantic begins to decline. The global effect is large long before sea level rise of 5 m is reached. Meltwater reduces global warming about half by the time sea level rise reaches 1.7 m. Cooling due to ice melt more than eliminates A1B warming in large areas of the globe.

The large cooling effect of ice melt does not decrease much as the ice melting rate varies between doubling times of 5, 10 or 20 years (Fig. 10a). In other words, the cumulative ice sheet melt, rather than the rate of ice melt, largely determines the climate impact for the range of melt rates covered by 5, 10 and 20 year doubling times. Thus if ice sheet loss occurs even to an extent of 1.7 m sea level rise (Fig. 10b), a large impact on climate and climate change is predicted.

Greater global cooling occurs for freshwater injected on the Southern Ocean, but the cooling lasts much longer for North Atlantic injection (Fig. 10a). That persistent cooling, mainly at Northern Hemisphere middle and high latitudes (Fig. S8), is a consequence of the sensitivity, hysteresis effects, and long recovery time of the AMOC (Stocker and Wright, 1991; Rahmstorf, 1995 and earlier studies referenced therein). AMOC changes are described below.

When freshwater injection on the Southern Ocean is halted, global temperature jumps back within two decades to the value it would have had without any freshwater addition (Fig. 10a). Quick recovery is consistent with the Southern Ocean-centric picture of the global overturning circulation (Fig. 4, Talley, 2013), as the Southern Meridional Overturning Circulation (SMOC), driven by AABW formation, responds to change of the vertical stability of the ocean column near Antarctica (see Sect. 4) and the ocean mixed layer and sea ice have limited thermal inertia.

Global cooling due to ice melt causes a large increase in Earth's energy imbalance (Fig. 10b), adding about +2 W m^{-2}, which is larger than the imbalance caused by increasing GHGs. Thus, although the cold fresh water from ice sheet disintegration provides a negative feedback on regional and global surface temperature, it increases the planet's energy imbalance, thus providing more energy for ice melt (Hansen, 2005). This added energy is pumped into the ocean.

Increased downward energy flux at the top of the atmosphere is not located in the regions cooled by ice melt. On the contrary, those regions suffer a large reduction of net incoming energy (Fig. 11a). The regional energy reduction is a consequence of increased cloud cover (Fig. 11b) in response to the colder ocean surface. However,

the colder ocean surface reduces upward radiative, sensible and latent heat fluxes, thus causing a large (~ 50 $W m^{-2}$) increase of energy into the North Atlantic and a substantial but smaller flux into the Southern Ocean (Fig. 11c).

Below we conclude that the principal mechanism by which this ocean heat increases ice melt is via its effect on ice shelves. Discussion requires examination of how the freshwater injections alter the ocean circulation and internal ocean temperature.

3.4 Simulated AMOC

Broecker's articulation of likely effects of freshwater outbursts in the North Atlantic on ocean circulation and global climate (Broecker, 1990; Broecker et al., 1990) spurred quantitative studies with idealized ocean models (Stocker and Wright, 1991) and global atmosphere-ocean models (Manabe and Stouffer, 1995; Rahmstorf 1995, 1996). Scores of modeling studies have since been carried out, many reviewed by Barreiro et al. (2008), and observing systems are being developed to monitor modern changes in the AMOC (Carton and Hakkinen, 2011).

Our climate simulations in this section are 5 member ensembles of runs initiated at 25 year intervals at years 901–1001 of the control run. We chose this part of the control run because the planet is then in energy balance (Fig. S2), although by that time model drift had altered the slow deep ocean circulation. Some model drift away from initial climatological conditions is inevitable, as all models are imperfect, and we carry out the experiments with cognizance of model limitations. However, there is strong incentive to seek basic improvements in representation of physical processes to reduce drift in future versions of the model.

GHGs alone (scenario A1B) slow AMOC by the early 21st century (Fig. 12), but variability among individual runs (Fig. S9) would make definitive detection difficult at present. Freshwater injected onto the North Atlantic or in both hemispheres shuts down the AMOC (Fig. 12, right side). GHG amounts are fixed after 2100 and ice melt is zero, but after two centuries of stable climate forcing the AMOC has not recovered to its

earlier state. This slow recovery was found in the earliest simulations by Manabe and Stouffer (1994) and Rahmstorf (1995, 1996).

Freshwater injection already has a large impact when ice melt is a fraction of 1 m of sea level. By the time sea level rise reaches 59 cm (2065 in the present scenarios), when fresh water flux is 0.48 Sv, the impact on AMOC is already large, consistent with the substantial surface cooling in the North Atlantic (Fig. 9).

3.5 Comparison with prior simulations

AMOC sensitivity to GHG forcing has been examined extensively based on IPCC studies. Schmittner et al. (2005) found that AMOC weakened 25 ± 25 % by the end of the 21st century in 28 simulations of 9 different models forced by the A1B emission scenario. Gregory et al. (2005) found 10–50 % AMOC weakening in 11 models for CO_2 quadrupling (1 % yr^{-1} increase for 140 years), with largest decreases in models with strong AMOCs. Weaver et al. (2007) found a 15–31 % AMOC weakening for CO_2 quadrupling in a single model for 17 climate states differing in initial GHG amount. AMOC in our model weakens 30 % between 1990–2000 and 2090–2100, the period used by Schmittner et al. (2005), for A1B forcing (Fig. S9). Thus our model is more sensitive than the average, but within the range of other models, a conclusion that continues to be valid in comparison with 10 CMIP5 models (Cheng et al., 2013).

AMOC sensitivity to freshwater forcing has not been compared as systematically among models. Several studies find little impact of Greenland melt on AMOC (Huybrechts et al., 2002; Jungclaus et al., 2006; Vizcaino et al., 2008) while others find substantial North Atlantic cooling (Fichefet et al., 2003; Swingedouw et al., 2007; Hu et al., 2009, 2011). Studies with little impact calculated or assumed small ice sheet melt rates, e.g., Greenland contributed only 4 cm of sea level rise in the 21st century in the ice sheet model of Huybrechts et al. (2002). Fichefet et al. (2003), using nearly the same atmosphere-ocean model as Huybrechts et al. (2002) but a more responsive ice sheet model, found AMOC weakening from 20 to 13 Sv late in the 21st century, but separate contributions of ice melt and GHGs to AMOC slowdown were not defined.

Hu et al. (2009, 2011) use the A1B scenario and freshwater from Greenland starting at 1 mm sea level per year increasing 7 % yr^{-1}, similar to our 10 year doubling case. Hu et al. keep the melt rate constant after it reaches 0.3 Sv (in 2050), yielding 1.65 m sea level rise in 2100 and 4.2 m in 2200. Global warming found by Hu et al. (2009, 2010) for scenario A1B resembles our result but is 20–30 % smaller (compare Fig. 2b of Hu et al., 2009 to our Fig. 9), and cooling they obtain from the freshwater flux is moderately less than that in our model. AMOC is slowed about one-third by the latter 21st century in the Hu et al. (2011) 7 % yr^{-1} experiment, comparable to our result.

General consistency holds for other quantities, such as changes of precipitation. Our model yields southward shifting of the Inter-Tropical Convergence Zone (ITCZ) and intensification of the subtropical dry region with increasing GHGs (Fig. S10), as has been reported in modeling studies of Swingedouw et al. (2007, 2009) and others (IPCC, 2013). These effects are intensified by ice melt and cooling in the North Atlantic region (Fig. S10).

A recent 5-model study (Swingedouw et al., 2014) finds a small effect on AMOC for 0.1 Sv Greenland freshwater flux added in 2050 to simulations with a strong GHG forcing. Our larger response is likely due, at least in part, to our freshwater flux reaching several tenths of a Sv.

Freshwater sensitivity in our model is similar to an earlier version of the model used to simulate the 8.2 ky b2k freshwater event associated with demise of the Hudson Bay ice dome (LeGrande et al., 2006). The ~50 % AMOC slowdown in that model, in response to forcings of 2.5–5 Sv years indicated by geologic and paleohydraulic studies (e.g., Clarke et al, 2004), is consistent with indications from isotope-enabled analyses of the 8.2 ky event (LeGrande and Schmidt, 2008) and sediment records from the northwest Atlantic (Kleiven et al., 2008). The 1–2 century AMOC recovery time in numerical experiments (LeGrande and Schmidt, 2008) seems consistent with the 160 year duration of the 8.2 ky cooling event (Rasmussen et al., 2013).

3.6 Storm-related model diagnostics

Ice melt in the North Atlantic creates a substantial increment toward higher sea level pressure in the North Atlantic region in all seasons (Fig. 13). In the summer the added surface pressure strengthens and moves northward the Bermuda high pressure system (Fig. S3). Circulation around the high pressure creates strong prevailing northeasterly winds in the North Atlantic at the latitudes of Bermuda and the Bahamas. A1B climate forcing alone (top row of Fig. S11) has only a small impact on the winds, but cold meltwater in the North Atlantic causes a strengthening and poleward shift of the high pressure.

The high pressure in the model is located further east than appropriate for producing the fastest possible winds at the Bahamas. Our coarse resolution ($4^\circ \times 5^\circ$) model, which slightly misplaces the pressure maximum for today's climate, may be partly responsible for the displacement. However, the location of high pressure also depends meltwater placement, which we spread uniformly over all longitudes in the North Atlantic between 65° W and 15° E and on specific location of ocean currents and surface temperature during the Eemian.

Our results at least imply that strong cooling in the North Atlantic from AMOC shutdown does create higher wind speed. It would be useful to carry out more detailed studies with higher resolution climate models including the most realistic possible distribution of meltwater.

The increment in seasonal mean wind speed of the northeasterlies relative to preindustrial conditions is as much as 10–20 %. Such a percentage increase of wind speed in a storm translates into an increase of storm power dissipation by a factor ~1.4–2, because wind power dissipation is proportional to the cube of wind speed (Emanuel, 1987, 2005). However, our simulated changes refer to seasonal mean winds averaged over large grid-boxes, not individual storms.

A blocking high pressure system in the North Atlantic creating consistent strong northeasterly flow would provide wave action that may have contributed to the chevron

ridge formation in the Bahamas and Bermuda. This blocking high pressure system could contribute to powerful storm impacts in another way. In combination with the warm tropical conditions that existed in the late Eemian (Cortijo et al., 1999), and are expected in the future if GHGs continue to increase, this blocking high pressure could create a preferred alley for tropical storm tracks.

We assumed, in discussing the relevance of these experiments to Eemian climate, that effects of freshwater injection dominate over changing GHG amount, as seems likely because of the large freshwater effect on SSTs and sea level pressure. However, Eemian CO_2 was actually almost constant at ~275 ppm (Luthi et al., 2008). Thus, to isolate effects better, we now carry out simulations with fixed GHG amount, which helps clarify important feedback processes.

3.7 Pure freshwater experiments

Our pure freshwater experiments are 5 member ensembles starting at years 1001, 1101, 1201, 1301, and 1401 of the control run. Each experiment ran 300 years. Freshwater flux in the initial decade averaged 180 $km^3 yr^{-1}$ (0.5 mm sea level) in the hemisphere with ice melt and increased with a 10 year doubling time. Freshwater input is terminated when it reaches 0.5 m sea level rise per hemisphere for three 5-member ensembles: two ensembles with injection in the individual hemispheres and one ensemble with input in both hemispheres (1 m total sea level rise). Three additional ensembles were obtained by continuing freshwater injection until hemispheric sea level contributions reached 2.5 m. Here we provide a few model diagnostics central to discussions that follow. Additional results are provided in Figs. S12–S14.

The AMOC shuts down for Northern Hemisphere freshwater input yielding 2.5 m sea level rise (Fig. 14). By year 300, more than 200 years after cessation of all freshwater input, AMOC is still far from full recovery for this large freshwater input. On the other hand, freshwater input of 0.5 m does not cause full shutdown, and AMOC recovery occurs in less than a century.

Global temperature change (Fig. 15) reflects the fundamentally different impact of freshwater forcings of 0.5 and 2.5 m. The response also differs greatly depending on the hemisphere of the freshwater input. The case with freshwater forcing in both hemispheres is shown only in the Supplement because, to a good approximation, the response is simply the sum of the responses to the individual hemispheric forcings (see Figs. S12–S14). The sum of responses to hemispheric forcings moderately exceeds the response to global forcing.

Global cooling continues for centuries for the case with freshwater forcing sufficient to shut down the AMOC (Fig. 15). If the forcing is only 0.5 m of sea level, the temperature recovers in a few decades. However, the freshwater forcing required to reach the tipping point of AMOC shutdown may be less in the real world than in our model, as discussed below. Global cooling due to freshwater input on the Southern Ocean recovers in a few years after freshwater input ceases (Fig. 15), for both the smaller (0.5 m of sea level) and larger (2.5 m) freshwater forcings.

Injection of a large amount of surface freshwater in either hemisphere has a notable impact on heat uptake by the ocean and the internal ocean heat distribution (Fig. 16). Despite continuous injection of a large amount of very cold (−15 °C) water in these pure freshwater experiments, substantial portions of the ocean interior become warmer. Tropical and Southern Hemisphere warming is the well-known effect of reduced heat transport to northern latitudes in response to the AMOC shutdown (Rahmstorf, 1996; Barreiro et al., 2008).

However, deep warming in the Southern Ocean may have greater consequences. Warming is maximum at grounding line depths (~1–2 km) of Antarctic ice shelves (Rignot and Jacobs, 2002). Ice shelves near their grounding lines (Fig. 13 of Jenkins and Doake, 1991) are sensitive to temperature of the proximate ocean, with ice shelf melting increasing 1 m per year for each 0.1 °C temperature increase (Rignot and Jacobs, 2002). The foot of an ice shelf provides most of the restraining force that ice shelves exert on landward ice (Fig. 14 of Jenkins and Doake, 1991), making ice near the grounding line the buttress of the buttress. Pritchard et al. (2012) deduce from

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

satellite altimetry that ice shelf melt has primary control of Antarctic ice sheet mass loss.

Thus we examine our simulations in more detail (Fig. 17). The pure freshwater experiments add 5 mm sea level in the first decade (requiring an initial 0.346 mm yr^{-1} for 10 year doubling), 10 mm in the second decade, and so on (Fig. 17a). Cumulative freshwater injection reaches 0.5 m in year 68 and 2.5 m in year 90.

AABW formation is reduced ~20 % by year 68 and ~50 % by year 90 (Fig. 17b). When freshwater injection ceases, AABW formation rapidly regains full strength, in contrast to the long delay in reestablishing NADW formation after AMOC shutdown. The response time of the Southern Ocean mixed layer dictates the recovery time for AABW formation. Thus rapid recovery also applies to ocean temperature at depths of ice shelf grounding lines (Fig. 17c).

The rapid response of the SMOC (within a decade) to a change of the density of the Southern Ocean mixed layer implies that the rate of freshwater addition to the mixed layer is the driving factor. We will argue below that our model, because of excessive small scale mixing, probably understates the mixed layer and SMOC sensitivities to freshwater flux change, and in a later section we present evidence that the real world is responding more quickly than the model.

Sea ice cover, accurately monitored from satellites since the late 1970s, is a key diagnostic of the ocean surface layer. Increasing sea ice cover, we show below, is a powerful feedback that amplifies ice shelf melt. Freshwater flux has little effect on our simulated Northern Hemisphere sea ice until the 7th decade of freshwater growth (Fig. 17d), but Southern Hemisphere sea ice is more sensitive, with substantial response in the 5th decade and large response in the 6th decade.

Is 5th decade freshwater flux (2880 Gt yr^{-1}) of relevance to today's world? Yes, we will conclude, the Southern Ocean is already experiencing at least "5th decade" freshwater forcing. We explain the basis of that conclusion below, and then make a climate simulation for the 21st century with more realistic forcings than in our prior simulations.

4 Simulations to 2100 with modified (more realistic) forcings

Recent data imply that current ice melt is larger than assumed in our 1850–2300 climate simulations. Thus we make an additional simulation and use the opportunity to make minor improvements in the radiative forcing.

4.1 Advanced (earlier) freshwater injection

Atmosphere-ocean climate models, including ours, commonly include a fixed freshwater flux from the Greenland and Antarctic ice sheets to the ocean. This flux is chosen to balance snow accumulation in the model's control run, with the rationale that approximate balance is expected between net accumulation and mass loss including icebergs and ice shelf melting. Global warming creates a mass imbalance that we want to investigate. Ice sheet models can calculate the imbalance, but it is unclear how reliably ice sheet models simulate ice sheet disintegration. We forgo ice sheet modeling, instead adding a growing freshwater amount to polar oceans with alternative growth rates and initial freshwater amount estimated from available data.

Change of freshwater flux on the ocean in a warming world with shrinking ice sheets consists of two terms, Term 1 being net ice melt and Term 2 being change of P-E (precipitation minus evaporation) over the relevant ocean. Term 1 includes land based ice mass loss, which can be detected by satellite gravity measurements, loss of ice shelves, and net sea ice mass change. Term 2 is calculated in a climate model forced by changing atmospheric composition, but it is not included in our pure freshwater experiments that have no global warming.

IPCC (2013, Chapter 4) estimated land ice loss in Antarctica that increased from 30 Gt yr^{-1} in 1992–2001 to 147 Gt yr^{-1} in 2002–2011 and in Greenland from 34 to 215 Gt yr^{-1}, with uncertainties discussed by IPCC (2013). Gravity satellite data suggest Greenland ice sheet mass loss ~300–400 Gt yr^{-1} in the past few years (Barletta et al., 2013). A newer analysis of gravity data for 2003–2013 (Velicogna et al., 2014),

Exhibit 3 to Declaration of Dr. James E. Hansen

discussed in more detail in Sect. 6, finds a Greenland mass loss $280 \pm 58\,\mathrm{Gt\,yr^{-1}}$ and Antarctic mass loss $67 \pm 44\,\mathrm{Gt\,yr^{-1}}$.

One estimate of net ice loss from Antarctica, including ice shelves, is obtained by surveying and adding the mass flux from all ice shelves and comparing this freshwater mass loss with the freshwater mass gain from the continental surface mass budget. Rignot et al. (2013) and Depoorter et al. (2013) independently assessed the freshwater mass fluxes from Antarctic ice shelves. Their respective estimates for the basal melt are 1500 ± 237 and $1454 \pm 174\,\mathrm{Gt\,yr^{-1}}$. Their respective estimates for calving are 1265 ± 139 and $1321 \pm 144\,\mathrm{Gt\,yr^{-1}}$.

This estimated freshwater loss via the ice shelves ($\sim 2800\,\mathrm{Gt\,yr^{-1}}$) is larger than freshwater gain by the Antarctic surface. Vaughan et al. (1999) estimated the net surface mass balance of the continent as $+1811$ and $+2288\,\mathrm{Gt\,yr^{-1}}$ including precipitation on ice shelves. IPCC (2013) estimates the net Antarctic surface mass balance as $+1983 \pm 122\,\mathrm{Gt\,yr^{-1}}$ excluding ice shelves. Thus comparison of continental freshwater input with ice shelf output suggests a net export of freshwater to the Southern Ocean of several hundred $\mathrm{Gt\,yr^{-1}}$ in recent years. However, substantial uncertainty exists in the difference between these two large numbers.

A remarkable independent evaluation has recently been achieved by Rye et al. (2014) using satellite measured changes of sea level around Antarctica in the period 1992–2011. Sea level along the Antarctic coast rose $2\,\mathrm{mm\,yr^{-1}}$ faster than the regional mean sea level rise in the Southern Ocean south of 50° S, an effect that they conclude is almost entirely a steric adjustment caused by accelerating freshwater discharge from Antarctica. They conclude that an excess freshwater input of $430 \pm 230\,\mathrm{Gt\,yr^{-1}}$, above the rate needed to maintain a steady ocean salinity, is required. Rye et al. (2014) note that these values constitute a lower bound for the actual excess discharge above a "steady salinity" rate, because numerous in situ data, discussed below, indicate that freshening began earlier than 1992.

Term 2, change of P-E over the Southern Ocean relative to its pre-industrial amount, is large in all climate simulations (IPCC, 2013). In our ensemble of runs (using ob-

served GHGs for 1850–2003 and scenario A1B thereafter) the increase of P-E in the decade 2011–2020, relative to the control run, was in the range 3500 to $4000\,\mathrm{Gt\,yr^{-1}}$, as mean precipitation over the Southern Ocean increased $\sim 35\,\mathrm{mm\,yr^{-1}}$ and evaporation decreased $\sim 3\,\mathrm{mm\,yr^{-1}}$.

Increasing ice melt and increasing P-E are climate feedbacks, their growth in recent decades driven by global warming. Our pure freshwater simulations indicate that their sum, at least $4000\,\mathrm{Gt\,yr^{-1}}$, is sufficient to affect ocean circulation, sea ice cover, and surface temperature, which can spur other climate feedbacks. We investigate these feedbacks via climate simulations using improved estimates of freshwater flux from ice melt. P-E is computed by the model.

We take freshwater injection to be $720\,\mathrm{Gt\,yr^{-1}}$ from Antarctica and $360\,\mathrm{Gt\,yr^{-1}}$ in the North Atlantic in 2011, with injection rates at earlier and later times defined by assumption of a 10 year doubling time. Resulting mean freshwater injection around Antarctica in 1992–2011 is $\sim 400\,\mathrm{Gt\,yr^{-1}}$, similar to the estimate of Rye et al. (2014). A recent estimate of $310 \pm 74\,\mathrm{km^3}$ volume loss of floating Antarctic ice shelves in 2003–2012 (Paolo et al., 2015) is not inconsistent, as the radar altimeter data employed for ice shelves does not include contributions from the ice sheet or fast ice tongues at the ice shelf grounding line. Greenland ice sheet mass loss provides most of the assumed $360\,\mathrm{Gt\,yr^{-1}}$ freshwater, and this would be supplemented by shrinking ice shelves (Rignot and Steffen, 2008) and small ice caps in the North Atlantic and west of Greenland (Ohmura, 2009) that are losing mass (Abdalati et al., 2004; Bahr et al., 2009).

We add the freshwater around Antarctica at coastal grid boxes (Fig. S15) guided by the data of Rignot et al. (2013) and Depoorter et al. (2013), the flux in the western hemisphere from the Weddell Sea to the Ross Sea being about three times larger than for the rest of the coastline. Specified freshwater flux around Greenland is similar on the east and west coasts, and small along the north coast (Fig. S15).

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

4.2 Modified radiative forcings

Actual GHG forcing has grown slower than scenario A1B, because growth of CH_4 and minor gases declined after IPCC scenarios were defined (Fig. 5, Hansen et al., 2013c, update at http://www.columbia.edu/~mhs119/GHGs/). As a simple improvement we decreased the A1B CH_4 scenario during 2003–2013 such that subsequent CH_4 is reduced 100 ppb, thus decreasing the radiative forcing $\sim 0.05\,\mathrm{W\,m^{-2}}$.

Stratospheric aerosol forcing to 2014 uses the data set of Sato et al. (1993) as updated at http://www.columbia.edu/~mhs119/StratAer/. Future years have constant aerosol optical depth 0.0052 yielding effective forcing $-0.12\,\mathrm{W\,m^{-2}}$, implemented by using fixed 1997 aerosol data. Tropospheric aerosol growth is assumed to slow smoothly, leveling out at $-2\,\mathrm{W\,m^{-2}}$ in 2100. Future solar forcing is assumed to have an 11 year cycle with amplitude $0.25\,\mathrm{W\,m^{-2}}$. Net forcing exceeds $5\,\mathrm{W\,m^{-2}}$ by the end of the 21st century, about three times the current forcing (Fig. 18).

4.3 Climate simulations with modified forcings

Global temperature has a peak at +1.2 °C in the 2040s for the modified forcings (Fig. 19). Ice melt cooling is advanced as global ice melt reaches 1 m of sea level in 2060, 1/3 from Greenland and 2/3 from Antarctica. Actual sea level rise could be less than 1 m, depending on the portion of melt from ice shelves (which has little effect on sea level), but contributions from ocean thermal expansion and mountain glacier melt would probably make global mean sea level rise at least of the order of 1 m.

Global temperature rise resumes in the 2060s after total cessation of the freshwater injection. However, termination of freshwater injection is imposed only for the sake of analyzing climate mechanisms, not with expectation that a sudden halt of ice sheet disintegration is realistic.

Global temperature becomes an unreliable diagnostic of planetary condition as the ice melt rate increases. Global energy imbalance (Fig. 19b) is a more meaningful measure of planetary status as well as an estimate of the climate forcing change required

to stabilize climate. Our calculated present energy imbalance of $\sim 0.8\,\mathrm{W\,m^{-2}}$ (Fig. 19b) is larger than the observed $0.58 \pm 0.15\,\mathrm{W\,m^{-2}}$ during 2005–2010 (Hansen et al., 2011). The discrepancy is likely accounted for by excessive ocean heat uptake at low latitudes in our model, a problem related to the model's slow surface response time (Fig. 7) that may be caused by excessive small scale ocean mixing.

Large scale regional cooling occurs in the North Atlantic and Southern Oceans by mid-century (Fig. 20) for 10 year doubling of freshwater injection. A 20 year doubling places similar cooling near the end of this century, 40 years earlier than in our prior simulations (Fig. 10), as the factor of four increase of current freshwater from Antarctica is a 40 year advance.

The critical issue is whether human-spurred ice sheet mass loss can be approximated as an exponential process during the next few decades. Such nonlinear behavior depends upon amplifying feedbacks, which, indeed, our climate simulations reveal in the Southern Ocean.

4.4 Southern Ocean feedbacks

Amplifying feedbacks in the Southern Ocean and atmosphere contribute to dramatic climate change in our simulations (Fig. 20). We first summarize the feedbacks to identify processes that must be simulated well to draw valid conclusions. While recognizing the complexity of the global ocean circulation (Lozier, 2012; Lumpkin and Speer, 2007; Marshall and Speer, 2012; Munk and Wunsch, 1998; Orsi et al., 1999; Sheen et al., 2014; Talley, 2013; Wunsch and Ferrari, 2004), we use a simple two-dimensional representation to discuss the feedbacks.

Climate change includes slowdown of AABW formation, indeed shutdown by midcentury if freshwater injection increases with a doubling time as short as 10 years (Fig. 21). Implications of AABW shutdown are so great that we must ask whether the mechanisms are simulated with sufficient realism in our climate model, which has coarse resolution and relevant deficiencies that we have noted. After discussing the feedbacks

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

here, we examine how well the processes are included in our model (Sect. 4.5). Paleoclimate data (Sect. 5) provides much insight about these processes and modern observations (Sect. 7) show that these feedbacks are already underway.

Large-scale climate processes affecting ice sheets are sketched in Fig. 22. The role of the ocean circulation in the global energy and carbon cycles is captured to a useful extent by the two-dimensional (zonal mean) overturning circulation featuring deep water (NADW) and bottom water (AABW) formation in the polar regions. Marshall and Speer (2012) discuss the circulation based in part on tracer data and analyses by Lumpkin and Speer (2007). Talley (2013) extends the discussion with diagrams clarifying the role of the Pacific and Indian Oceans.

Wunsch (2002) emphasizes that the ocean circulation is driven primarily by atmospheric winds and secondarily by tidal stirring. The energy drawing deep water toward the surface in the Southern Ocean (Fig. 22) is provided by strong circumpolar westerly winds. This complex global thermohaline circulation can be altered by natural and human-made forcings, including freshwater injection from ice sheets, which stimulate powerful feedback processes.

A key feedback concerns the effect of cold freshwater injection on ocean temperature at ice shelf grounding lines. In our "pure freshwater" simulations the freshwater added to the Southern Ocean acts as a lid that reduces ventilation of ocean heat to the atmosphere and space. Warming is largest at depths near ice shelf grounding lines, the portion of the ice shelf that provides most of the restraining force that limits the rate of ice sheet discharge to the ocean (Fig. 14 of Jenkins and Doake, 1991). Melting at ice shelf grounding lines in West Antarctica and Wilkes Basin in East Antarctica has potential to result in rapid, nonlinear sea level rise because these basins have retrograde beds (beds sloping inland), a configuration with potential for unstable grounding line retreat and substantial ice sheet disintegration (Mercer, 1978), as discussed further below. Multiple submarine valleys make much of the Greenland ice sheet vulnerable to thermal forcing by a warming ocean (Morlighem et al., 2014), but with a few exceptions

(Khan et al., 2014) the valleys are prograde and thus rapid nonlinear growth of ice melt is not likely.

Another feedback occurs via the effect of surface and atmospheric cooling on precipitation and evaporation over the Southern Ocean. In climate simulations that do not include increasing freshwater injection in the Southern Ocean (IPCC, 2013), it is found that snowfall on Antarctica increases substantially in the 21st century, thus providing a negative term to sea level change. Frieler et al. (2015) assert that 35 global climate models are consistent in showing that a warming climate will yield increasing Antarctic snow accumulation, but this paleo "affirmation" refers to slowly changing climate in quasi-equilibrium with ocean boundary conditions. In our experiments with growing freshwater injection the increasing sea ice cover and cooling of the Southern Ocean surface and atmosphere cause the increased precipitation to occur over the Southern Ocean, rather than over Antarctica. This feedback not only reduces any increase of snowfall over Antarctica, it also provides a large freshening term to the surface of the Southern Ocean, thus magnifying the direct freshening effect from increasing ice sheet melt.

4.5 Model's ability to simulate these feedbacks

Realistic representation of these feedbacks places requirements on both the atmosphere and ocean components of our climate model. We discuss first the atmosphere, then the ocean.

There are two main requirements on the atmospheric model. First, it must simulate well P-E and changes of P-E, because of its importance for ocean circulation and the amplifying feedback in the Southern Ocean. Precise verification of P-E is difficult to attain, but the ultimate model requirement is that it produce realistic sea surface salinity (SSS) patterns and ongoing changes.

Simulated P-E (Fig. S16b) agrees well with meteorological reanalysis (Fig. 3.4b, IPCC, 2013). Simulated global sea surface salinity (SSS) patterns (Fig. S16a) agree well with global ocean surface salinity patterns (Antonov et al., 2010 and Fig. 3.4a,

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

IPCC, 2013). SSS trends in our simulation (Fig. S16c), with the Pacific on average becoming fresher while most of the Atlantic and the subtropics in the Southern Hemisphere become saltier, are consistent with observed salinity trends (Durack and Wijffels, 2010). Recent freshening of the Southern Ocean in our simulation is somewhat less than in observed data (IPCC, Figs. 3.4c and 3.4d), implying that the amplifying feedback may be *under*estimated in our simulation. A likely reason for that is discussed below in conjunction with observed sea ice change.

The second requirement is that the atmospheric model simulate well winds and their changes, because these drive the ocean. Thus the model must simulate well atmospheric pressure patterns and changes in response to climate forcings. A test is provided by observed changes of the Southern Annular Mode (SAM), with a decrease of surface pressure near Antarctica and a small increase at mid-latitudes (Marshall, 2003) that D. Thompson et al. (2011) relate to stratospheric ozone loss and increasing GHGs. Our climate forcing (Fig. 18) includes ozone change (Fig. 2, Hansen et al., 2007a) with stratospheric ozone depletion in 1979–1997 and constant ozone thereafter. Our model produces a trend toward the high index polarity of SAM (Fig. S17) similar to observations, although perhaps a slightly smaller change than observed (compare Fig. S17 with Fig. 3 of Marshall, 2003). SAM continues to increase in our model after ozone stabilizes (Fig. S17), suggesting that GHGs may provide a larger portion of the SAM response in our model than in the model study of D. Thompson et al. (2011). It would not be surprising if the stratospheric dynamical response to ozone change were weak in our model, given the coarse resolution and simplified representation of atmospheric drag and dynamical effects in the stratosphere (Hansen et al., 2007a), but that is not a major concern for our present purposes.

The ocean model must be able to simulate realistically the ocean's overturning circulation and its response to forcings including freshwater additions. Heuze et al. (2013, 2015) point out that simulated deep convection in the Southern Ocean is unrealistic in most models, with AABW formation occurring in the open ocean where it rarely occurs in nature. Our present ocean model contains significant improvements (see Sect. 3.1)

compared to the GISS E2-R model that Heuze et al. include in their comparisons. Thus we show (Fig. 23) the maximum mixed layer depth in winter (February in the Northern Hemisphere and August in the Southern Hemisphere) using the same criterion as Heuze et al. to define the mixed layer depth, i.e., the layers with a density difference from the ocean surface layer less than 0.03 $\mathrm{kg\,m^{-3}}$.

Southern Ocean mixing in the model reaches a depth of ∼ 500 m in a wide belt near 60° S stretching west from the southern tip of South America, with similar depths south of Australia. These open ocean mixed layer depths compare favorably with observations shown in Fig. 2a of Heuze et al. (2015), based on data of de Boyer Montegut et al. (2004). There is no open ocean deep convection in our model.

Deep convection occurs only along the coast of Antarctica (Fig. 23). Coastal grid boxes on the continental shelf are a realistic location for AABW formation. Orsi et al. (1999) suggest that most AABW is formed on shelves around the Weddell-Enderby Basin (60 %) and shelves of the Adelie-Wilkes Coast and Ross Sea (40 %). Our model produces mixing down to the shelf in those locations (Fig. 23b), but also on the Amery Ice Shelf near the location where Ohshima et al. (2013) identified AABW production, which they term Cape Darnley Bottom Water.

However, with our coarse 4° × 5° stair step to the ocean bottom the AABW cannot readily slide down the slope to the ocean floor. As a result, the denser water from the shelf mixes into the open ocean grid boxes, making our modeled Southern Ocean less stratified than the real world (cf. temporal drift of Southern Ocean salinity in Fig. S18), because the denser water must move several degrees of latitude horizontally before it can move deeper. Nevertheless, our Southern Ocean is sufficiently stratified to avoid the unrealistic open ocean convection that infects many models (Heuze et al., 2013).

Orsi et al. (1999) estimate the AABW formation rate in several ways, obtaining values in the range 8–12 Sv, larger than our modeled 5–6 Sv (Fig. 21). However, as in most models (Heuze et al., 2015) our SMOC diagnostic (Fig. 21) is the mean (Eulerian) circulation, i.e., excluding eddy-induced transport. Rerun of a 20 year segment of our control run to save eddy-induced changes reveals an increase of SMOC at 72° S by 1–

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

2 Sv, with negligible change at middle and low latitudes, making our simulated transport close to the range estimated by Orsi et al. (1999).

We conclude that the climate model can potentially simulate Southern Ocean feedbacks that magnify the effect of freshwater injection onto the Southern Ocean: the P-E feedback that wrenches global-warming-enhanced water vapor from the air before it reaches the Antarctic continent and the AABW slowdown that traps deep ocean heat, leaving that heat at levels where it accelerates ice shelf melting. Indeed, we will argue that both of these feedbacks are probably underestimated in our current model.

The model seems less capable in Northern Hemisphere polar regions. Deep convection today is believed to occur mainly in the Greenland-Iceland-Norwegian (GIN) Sea and at the southern end of Baffin Bay (Fig. 2b, Heuze et al., 2015). In our model, perhaps because of excessive sea ice in those regions, open ocean deep convection occurs to the southeast of the southern tip of Greenland and at less deep grid boxes between that location and the United Kingdom (Fig. 23). Mixing reaching the ocean floor on the Siberian Coast in our model (Fig. 23) may be realistic, as coastal polynya are observed on the Siberian continental shelf (D. Bauch et al., 2012). However, the winter mixed layer on the Alaska south coast is unrealistically deep (Fig. 23). These model limitations must be kept in mind in interpreting simulated Northern Hemisphere climate change.

5 Implications of paleoclimate data

Paleoclimate data are essential for understanding the major climate feedbacks. Processes of special importance are: (1) the role of the Southern Ocean in ventilating the deep ocean, affecting CO_2 control of global temperature, and (2) the role of subsurface ocean warming in ice shelf melt, affecting ice sheet disintegration and sea level rise.

5.1 Paleoclimate context

Major glacial-interglacial climate oscillations are spurred by periodic variation of seasonal and geographical insolation (Hays et al., 1976). Insolation anomalies are caused by slow changes of the eccentricity of Earth's orbit, tilt of Earth's spin axis, and precession of the equinoxes, thus the day of year at which Earth is closest to the Sun, with dominant periodicities near 100 000, 40 000 and 20 000 years (Berger, 1978). These periods emerge in long climate records, yet a large fraction of climate variability at any site is stochastic (Wunsch, 2004; Lisiecki and Raymo, 2005). Such behavior is expected for a weakly-forced system characterized by amplifying feedbacks, complex dynamics, and multiple sources of inertia with a range of time scales.

Large glacial-interglacial climate change and stochastic variability are a result of two strong amplifying feedbacks, surface albedo and atmospheric CO_2. Orbit-induced insolation anomalies, per se, cause a climate forcing, i.e., an Earth energy imbalance, only of order 0.1 $W\,m^{-2}$, but the persistent regional insolation anomalies spur changes of ice sheet size and GHGs. The albedo and GHG changes arise as slow climate feedbacks, but they are the forcings that maintain a quasi-equilibrium climate state nearly in global radiative balance. Glacial-interglacial albedo and greenhouse forcings are each ~3 $W\,m^{-2}$ (Fig. 24e, f)[1]. These forcings fully account for glacial-interglacial global temperature change with a climate sensitivity 0.5–1 °C per $W\,m^{-2}$ (Hansen et al., 2008; Masson-Delmotte et al., 2010; Palaeosens, 2012).

The insolation anomaly peaking at 129.5 ky b2k (Fig. 24a) succeeded in removing ice sheets from North America and Eurasia and in driving atmospheric CO_2 up to

[1]Other parts of Fig. 24 are discussed later, but they are most informative if aligned together. In interpreting Fig. 24, note that long-lived greenhouse gas amounts in ice cores have global relevance, but ice core temperatures are local to Greenland and Antarctica. Also, because our analysis does not depend on absolute temperature, we do not need to convert the temperature proxy, $\delta^{18}O$, into an estimated absolute temperature. We include CH_4 and N_2O in the total GHG climate forcing, but we do not discuss the reasons for CH_4 and N_2O variability (see Schilt et al., 2010), because CO_2 provides ~80 % of the GHG forcing.

$\sim$ 285 ppm, as discussed below. However, smaller climate oscillations within the last glacial cycle are also instructive about ice feedbacks. Some of these oscillations are related to weak insolation anomalies and all are affected by predominately amplifying climate feedbacks.

Insolation anomalies peaking at 107 and 86 ky b2k (Fig. 24a) led to $\sim$ 40 m sea level rises at rates exceeding 1 m century^{-1} (Stirling et al., 1998; Cutler et al., 2003) in early MIS 5c and 5a (Fig. 24f), but CO_2 did not rise above 250 ppm and interglacial status was not achieved. CO_2 then continued on a 100 ky decline until $\sim$ 18 ky b2k. Sea level continued its long decline, in concert with CO_2, reaching a minimum at least 120 m below today's sea level (Peltier and Fairbanks, 2006; Lambeck et al., 2014).

Progress achieved by the paleoclimate and oceanographic research communities allows interpretation of the role of the Southern Ocean in the tight relationship between CO_2 and temperature, as well as discussion of the role of subsurface ocean warming in sea level rise. Both topics are needed to interpret end-Eemian climate change and ongoing climate change.

5.2 Southern Ocean and atmospheric CO_2

Reduced atmospheric CO_2 in glacial times, at least in substantial part, results from increased stratification of the Southern Ocean that reduces ventilation of the deep ocean (Toggweiler, 1999; Anderson et al., 2009; Skinner et al., 2010; Tschumi et al., 2011; Burke and Robinson, 2012; Schmitt et al., 2012; Marcott et al., 2014). Today the average "age" of deep water, i.e., the time since it left the ocean surface, is $\sim$ 1000 years (DeVries and Primeau, 2011), but it was more than twice that old during the last glacial maximum (Skinner et al., 2010). The Southern Ocean dominates exchange between the deep ocean and atmosphere because $\sim$ 80 % of deep water resurfaces in the Southern Ocean (Lumpkin and Speer, 2007), as westerly circumpolar winds and surface flow draw up deep water (Talley, 2013).

Mechanisms causing more rapid deep ocean ventilation during interglacials include warmer Antarctic climate that increases heat flux into the ocean and buoyancy mixing

that supports upwelling (Watson and Garabato, 2006), poleward shift of the westerlies (Toggweiler et al., 2006), and reduced sea ice (Keeling and Stephens, 2001). Fischer et al. (2010) question whether the latitudinal shift of westerlies is an important contributor; however, the basic point is the empirical fact that a warmer interglacial Southern Ocean produces faster ventilation of the deep ocean via a combination of mechanisms.

Poor ocean ventilation in glacial periods allows carbon to be sequestered via the "biological pump", the rain of organic matter from the surface ocean that affects burial of calcium carbonate in sediments (Sigman and Boyle, 2000). Dust-borne iron fertilization of the biological pump (Martin and Fitzwater, 1988) contributes to millennial and full glacial CO_2 drawdown (Martinez-Garcia et al., 2014). In concert, global cooling drives the simple "solubility pump", as the temperature dependence of CO_2 solubility increases dissolved inorganic carbon (Raven and Falkowski, 1999). The increased acidity of deep water makes it more corrosive to carbonate sediments, thus increasing ocean alkalinity and further lowering atmospheric CO_2 (Boyle, 1988).

Much remains to be learned about glacial-interglacial carbon cycle mechanisms. Carbon isotopes indicate that increased deep ocean ventilation during deglaciation from the last ice age caused a 30–35 ppm CO_2 increase within 2000 years (Schmitt et al., 2012; Tschumi et al., 2011). However, AMOC changes are associated with at least two rapid CO_2 increases of about 10 ppm, as revealed by a high resolution West Antarctic ice core (Marcott et al., 2014). Another indication of possible Atlantic involvement in the carbon cycle is the change of the North Atlantic's Western Boundary Undercurrent during the transition to full glacial conditions at $\sim$ 70 ky b2k when CO_2 dropped below 200 ppm (Fig. 24); the flow became stronger in the upper 2 km while the deeper circulation weakened (Thornalley et al., 2013). No doubt the terrestrial biosphere also contributes to atmospheric CO_2 change (Archer et al., 2000; Sigman and Boyle, 2000; Kohler et al., 2005; Menviel et al., 2012; Fischer et al., 2015). Nevertheless, it is reasonably clear that sequestration of CO_2 in the glacial ocean is the largest cause of glacial-interglacial CO_2 change, and ocean ventilation occurs mainly via the Southern Ocean.

Southern Ocean ventilation, as the dominant cause of atmospheric CO_2 change, helps explain temperature-CO_2 leads and lags. Temperature and CO_2 rises are almost congruent at ice age terminations (Masson-Delmotte, 2010; Pedro et al., 2012; Parrenin et al., 2013). Southern Ocean temperature is expected to lead, spurring deep ocean ventilation and atmospheric CO_2 increase, with global temperature following. Termination I is dated best and Shakun et al. (2012) have reconstructed global temperature then, finding evidence for this expected order of events.

Correlation of $\delta^{18}O$ and CO_2 over the past 140 ky (Fig. 24c) is 84.4 % with CO_2 lagging by 760 years. For the period 100–20 ky b2k, which excludes the two terminations, the correlation is 77.5 % with CO_2 lagging by 1040 years. Briefer lag for the longer period and longer lag during glacial inception are consistent with the rapid deep ocean ventilation that occurs at terminations.

5.3 CO_2 as climate control knob

CO_2 is the principal determinant of Earth's climate state, the "control knob" that sets global mean temperature (Lacis et al., 2010, 2013). The degree of control is shown by comparison of CO_2 amount with Antarctic temperature for the past 800 000 years (Fig. 25a). Control should be even tighter for global temperature than for Antarctic temperature, because of regional anomalies such as Antarctic temperature overshoot at terminations (Masson-Delmotte, 2006, 2010), but global data are not available.[2]

[2]The tight fit of CO_2 and Antarctic temperature (Fig. 25a) implies an equilibrium Antarctic sensitivity 20 °C for 2× CO_2 (4 W m^{-2}) forcing (200 → 300 ppm forcing is ~ 2.3 W m^{-2}, Table 1 of Hansen et al., 2000), thus 10 °C global climate sensitivity (Antarctic temperature change is ~ twice global change) with CO_2 taken as the ultimate control knob, i.e., if snow/ice area and other GHGs are taken to be slaves to CO_2-driven climate change. This implies a conventional climate sensitivity of 4 °C for 2× CO_2, as GHG and albedo forcings are similar for glacial-to-interglacial climate change and non-CO_2 GHGs account for ~ 20 % of the GHG forcing. The inferred sensitivity is reduced to 2.5–3 °C for 2× CO_2 if, as some studies suggest, global mean glacial-interglacial temperature change is only about one-third of the Antarctic temperature change (Palaeosens, 2012; Hansen et al., 2013b).

The CO_2 dial must be turned to ~ 260 ppm to achieve a Holocene-level interglacial. CO_2 ~ 250 ppm was sufficient for quasi-interglacials in the period 800–450 ky b2k, with sea level 10–25 m lower than in the Holocene (Fig. S18 of Hansen et al., 2008). Interglacials with CO_2 ~ 280 ppm, i.e., the Eemian and Holsteinian (~ 400 ky b2k), were warmer than the Holocene and had sea level at least several meters higher than today.

CO_2 and albedo change are closely congruent over the last 800 000 years (Fig. S18 of Hansen et al., 2008). GHG and albedo forcings, which are both amplifying feedbacks that boost each other, are each of amplitude ~ 3 W m^{-2}. So why do we say that CO_2 is the control knob?

First, CO_2, in addition to being a slow climate feedback, changes independently of climate. Natural CO_2 change includes increase to ~ 1000 ppm about 50 million years ago (Zachos et al., 2001) as a result of plate tectonics, specifically volcanic emissions associated with movement of the Indian plate across the Tethys Ocean and collision with Asia (Kent and Muttoni, 2008). Humankind, mainly by burning fossil fuels, also moves the CO_2 control knob.

Second, CO_2 is more recalcitrant than snow and ice, i.e., its response time is longer. CO_2 inserted into the climate system, by humans or plate tectonics, remains in the climate system of order 100 000 years before full removal by weathering (Archer, 2005). Even CO_2 exchange between the atmosphere (where it affects climate) and ocean has a lag of the order a millennium (Fig. 24). In contrast, correlations of paleo temperatures and sea level show that lag of sea level change behind temperature is of order a century, not a millennium (Grant et al., 2012).

We suggest that limitations on the speed of ice volume (thus sea level) changes in the paleo record are more a consequence of the pace of orbital changes and CO_2 changes, as opposed to being a result of lethargic ice physics. "Fast" changes of CO_2 have been identified, e.g., an increase of ~ 10 ppm in about a century at ~ 39.6 ky b2k (Ahn et al., 2012) and three increases of 10–15 ppm each within 1–2 centuries during

Exhibit 3 to Declaration of Dr. James E. Hansen

Exhibit A 89

the deglaciation following the last ice age (Marcott et al., 2014), but the magnitude of these CO_2 increases is not sufficient to provide a good empirical test of ice sheet sensitivity to the CO_2 forcing.

Supremacy of SMOC, the Southern Ocean meridional overturning circulation, in affecting the CO_2 control knob and thus glacial-interglacial change is contrary to the idea that AMOC is a prime driver that flips global climate between quasi-stable glacial and interglacial states, yet AMOC retains a significant role. AMOC can affect CO_2 via the volume and residence time of NADW, but its largest effect is probably via its impact on the Southern Ocean. When AMOC is not shut down it cools the Southern Hemisphere, transferring heat from the Southern to the Northern Hemisphere at a rate ~ 1 petawatt, which is ~ 4 W m^{-2} averaged over a hemisphere (Crowley, 1992). However, the Southern Ocean slowly warms when AMOC shuts (or slows) down; the response time is of the order of 1000 years because of the Southern Ocean's large thermal inertia (Stocker and Johnson, 2003). These mechanisms largely account for the nature of the "bipolar seesaw" (Broecker, 1998; Stocker, 1998; Stenni et al., 2011; Landais et al., 2015), including the lag between AMOC slowdown and Antarctic warming.

5.4 Dansgaard–Oeschger events and subsurface ocean warming

The magnitude and rapidity of Greenland climate change during Dansgaard–Oeschger events would deter prediction of human-made climate effects, if D–O events remained a mystery. Instead, however, enough is now understood about D–O events that they provide insight related to the vulnerability of ice shelves and ice sheets, including the role of subsurface ocean warming.

Broecker (2000) inferred from the rapidity of D–O warmings that a reduction of sea ice cover was probably involved. Li et al. (2005, 2010) modeling showed that removal of Nordic Seas ice cover is needed to yield the magnitude of observed Greenland warming. The spatial gradient of D–O warming, with smaller warming in northwest Greenland, agrees with that picture (Guillevic et al., 2013; Buizert et al., 2014). Such sea ice change is consistent with changes in deuterium excess in Greenland ice cores at

D–O transitions, which indicate shifts of Greenland moisture source regions (Masson-Delmotte et al., 2005; Jouzel et al., 2007).

Fluckiger et al. (2006), Alvarez-Solas et al. (2010, 2011, 2013) and Marcott et al. (2011) noted modern and paleo data that point to ocean-ice shelf interaction as key to the ice discharge of accompanying Heinrich events, and they used a range of models to support this interpretation and overturn earlier suggestions of a central role for ice sheets via binge-purge oscillations (MacAyeal, 1993) or outburst flooding from subglacial reservoirs (Alley et al., 2006). Shaffer et al. (2004) and Petersen et al. (2013) conclude that subsurface ocean warming in the North Atlantic takes place during the stadial (cold) phase of all D–O events, and eventually this subsurface warming leads to ice shelf collapse or retreat, ice rafting, sea level rise, and sea ice changes. Rasmussen et al. (2003) examined ocean cores from the southeast Labrador Sea and found that for all 11 Heinrich events "... the icy surface water was overlying a relatively warm, poorly ventilated and nutrient rich intermediate water mass to a water depth of at least 1251 m." Collapse of a Greenland ice shelf fronting the Jakoshavn ice stream during the Younger Dryas cold event has been documented (Rinterknecht et al., 2014), apparently due to subsurface warming beneath the ice shelf leading to rapid discharge of icebergs.

Some D–O details are uncertain, e.g., the relation between changing sea ice cover and changing location of deep water formation (Rahmstorf, 1994) and whether an ice shelf between Greenland and Iceland contributed to the sea ice variability (Petersen et al., 2013). However, ocean-ice interactions emerge as key mechanisms, spurred by subsurface ocean warming, as ocean stratification slows but does not stop northward heat transport by AMOC.

We consider a specific D–O event for the sake of discussing mechanisms. D–O 22 cold phase, labeled C22 in ocean cores and coinciding with Heinrich H8 (Fig. 24), occurred as Northern Hemisphere insolation was rising (Fig. 24a). The North Atlantic surface was cooled by rapid ice discharge; sea level rose more than 40 m, a rate exceeding 1.6 m per century (Cutler et al., 2003). Ice discharge kept the North Atlantic

highly stratified, slowing AMOC. Antarctic warming from a slowed AMOC increases almost linearly with the length of the D–O cold phase (Fig. 3, EPICA Community Members, 2006; Fig. 6, Capron et al., 2010) because of the Southern Ocean's large heat capacity (Stocker and Johnson, 2003). Antarctic warming, aided by the 2500 year D–O 22 event, spurred SMOC enough to raise atmospheric CO_2 40 ppm (Fig. 24c).

As the Antarctic warmed, ocean heat transport to the North Atlantic would have increased, with most heat carried at depths below the surface layer. When the North Atlantic became warm enough at depth, stratification of cold fresh surface water eventually could not be maintained. The warming breakthrough may have included change of NADW formation location (Rahmstorf, 1994) or just large movement of the polar front. Surface warming east of Greenland removed most sea ice and Greenland warmed ~10 °C (Capron et al., 2010). As the warm phase of D–O 21 began, AMOC was pumping heat from the Antarctic into the Nordic seas and Earth must have been slightly out of energy balance, cooling to space, so both Antarctica and Greenland slowly cooled. Once the North Atlantic had cooled enough, sea formed east of Greenland again, ice sheets and ice shelves grew, sea level fell, and the polar front moved southward.

Sea level rise associated with D–O events covers a wide range. Sea level increases as large as ~40 m were associated with large insolation forcings at 107 and 86 ky b2k (Fig. 24). However, rapid sea level change occurred even when forcing was weak. Roche et al. (2004) conclude from analyses of $\delta^{18}O$ that H4, at a time of little insolation forcing (~40 ky b2k, Fig. 24), produced 1.9 ± 1.1 m sea level rise over 250 ± 150 years. Sea level rise as great as 10–15 m occurred in conjunction with some other D–O events during 65–30 ky b2k (Lambeck and Chappell, 2001; Yokoyama et al., 2001; Chappell, 2002).

Questions about possible D–O periodicity and external forcing were raised by a seeming 1470 year periodicity (Schulz, 2002). However, improved dating indicates that such periodicity is an artifact of ice core chronologies and not statistically significant (Ditlevsen et al., 2007) and inspection of Fig. 24b reveals a broad range of time scales. Instead, the data imply a climate system that responds sensitively to even weak forc-

ings and stochastic variability, both of which can spur amplifying feedbacks with a range of characteristic response times.

Two conclusions are especially germane. First, subsurface ocean warming is an effective mechanism for destabilizing ice shelves and thus the ice sheets buttressed by the ice shelves. Second, large rapid sea level rise can occur as a result of melting ice shelves.

However, ice shelves probably were more extensive during glacial times. So are today's ice sheets much more stable? The need to understand ice sheet vulnerability focuses attention on end-Eemian events, when ice sheets were comparable in size to today's ice sheets.

5.5 End-Eemian climate and sea level change

Termination II, ushering in the Eemian, was spurred by a late spring 60° N insolation anomaly peaking at +45 W m^{-2} at 129.5 ky b2k (Fig. 24a), the largest anomaly in at least the past 425 ky (Fig. 3, Hansen et al., 2007b). CO_2 and albedo forcings were mutually reinforcing. CO_2 began to rise before Antarctic $\delta^{18}O$, as deglaciation and warming began in the Northern Hemisphere. Most of the total CO_2 rise was presumably from deep ocean ventilation in the Southern Ocean, aided by meltwater that slowed the AMOC and thus helped to warm the Southern Ocean.

The northern insolation anomaly fell rapidly, becoming negative at 123.8 ky b2k (Fig. 24a). Northern Hemisphere ice sheets must have increased intermittently while Southern Hemisphere ice was still declining, consistent with minor, growing ice rafting events C27, C27a, C27b and C26 and a sea level minimum during 125–121 ky b2k (Sec 2.1). High Eemian climate variability in the Antarctic (Pol et al., 2014) was likely a result of the see-saw relation with North Atlantic events.

CO_2 (Fig. 24c) remained at ~270 ppm for almost 15 ky as the positive insolation anomaly on the Southern Ocean (Fig. 24a) kept the deep ocean ventilated. Sea level in the Red Sea analysis (Grant et al., 2012) shown in Fig. 24f seems to be in decline through the Eemian, but that must be a combination of dating and sea level error, as

numerous sea level analyses cited in Sect. 2.1 and others (e.g., Chen at al., 1991; Stirling et al., 1998; Cutler et al., 2003), indicate high sea level throughout the Eemian and allow a possible late-Eemian maximum. Chen et al. (1991), using a U-series dating with 2σ uncertainty $\pm$ 1.5 ky, found that the Eemian sea level high stand began between 132 and 129 ky b2k, lasted for 12 ky, and was followed by rapid sea level fall.

We assume that C26, the sharp cooling at 116.72 ky b2k in the NGRIP ice on the AICC2012 time scale, marks the end of fully interglacial Eemian conditions, described as 5e sensu stricto by Bauch and Erlenkeuser (2008). δ^{18}O in Antarctica was approaching a relative minimum (−46.7 per mil at EDML, see Fig. S19 for detail) and CO_2 was slowly declining at 263 ppm. In the next 300 years δ^{18}O increased to −45.2 and CO_2 increased by 13 ppm with lag ~ 1500 years, which we interpret as see-saw warming of the Southern Ocean in response to the C26-induced AMOC slowdown and resulting increased SMOC ventilation of CO_2.

Freshwater causing the C26 AMOC shutdown could not have been Greenland surface melt. Greenland was already 2000 years into a long cooling trend and the northern insolation anomaly was in the deepest minimum of the last 150 ky (Fig. 24a). Instead C26 was one event in a series, preceded by C27b and followed by C25, each a result of subsurface North Atlantic warming that melted ice shelves, causing ice sheets to discharge ice. Chapman and Shackleton (1999) did not find IRD from C26 in the mid-Atlantic, but Carlson et al. (2008) found a sharp increase in sediments near the southern tip of Greenland that they identified with C26.

We suggest that the Southern Hemisphere was the source for brief late-Eemian sea level rise. The positive warm-season insolation anomaly on the Southern Ocean and AMOC slowdown due to C26 added to Southern Ocean heat, causing ice shelf melt, ice sheet discharge, and sea level rise. Rapid Antarctica ice loss would cool the Southern Ocean and increase sea ice cover, which may have left telltale evidence in ice cores. Indeed, Masson-Delmotte et al. (2011) suggest that abrupt changes of δ^{18}O in the EDML and TALDICE ice cores (those most proximal to the coast) indicate a change in moisture origin, likely due to increased sea ice. Further analysis of Antarctic

data for the late Eemian might help pinpoint the melting and help assess vulnerability of Antarctic ice sheets to ocean warming, but this likely will require higher resolution models with more realistic sea ice distribution and seasonal change than our present model produces.

Terrestrial records in Northern Europe reveal rapid end-Eemian cooling. Sirocko et al. (2005) find cooling of 3 °C in summer and 5–10 °C in winter in southern Germany, annual layering in a dry Eifel maar lake revealing a 468 year period of aridity, dust storms, bushfires, and a decline of thermophilous trees. Similar cooling is found at other German sites and La Grande Pile in France (Kuhl and Litt, 2003). Authors in both cases interpret the changes as due to a southward shift of the polar front in the North Atlantic corresponding to C26. Cooling of this magnitude in northern Europe and increased aridity are found by Brayshaw et al. (2009) and Jackson et al. (2015) in simulations with high resolution climate models forced by AMOC shutdown.

While reiterating dating uncertainties, we note that the cool period with reduced NADW formation identified in recent high resolution ocean core studies for Eirik Drift site MD03-2664 (Fig. 3) near Greenland (Irvali et al., 2012; Galaasen et al., 2014) at ~ 117 ky b2k has length similar to the 468 year cold stormy period found in a German lake core (Sirocko et al., 2005). The Eirik core data show a brief return to near-Eemian conditions and then a slow decline, similar to the oscillation in the NGRIP ice core at 116.72 ky b2k on the AICC2012 time scale.

The principal site of NADW formation may have moved from the GIN Seas to just south of Greenland at end of the Eemian. Southward shift of NADW formation and the polar front is consistent with the sudden, large end-Eemian cooling in the North Atlantic and northern Europe, while cooling in Southern European was delayed by a few millennia (Brauer et al., 2007). Thus end-Eemian mid-latitude climate was characterized by an increased zonal temperature gradient, an important ingredient for strengthening storms.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

6 Impact of ice melt on storms

We can draw some conclusions about the effect of ice melt on winds and severe weather, despite limitations of our current climate model. Principal model limitations are its coarse resolution and unrealistic location of Northern Hemisphere deep water formation, this latter problem being likely related to the model's excessive Northern Hemisphere sea ice cover.

Despite these caveats, we have shown that the model realistically simulates zonal changes of sea level pressure in response to climate forcings. Specifically, the model yields a realistic trend to the positive phase of the Southern Annular Mode (SAM) in response to decrease of stratospheric ozone and increase of other GHGs (Fig. S17).

The modeled response of atmospheric pressure to the cooling effect of ice melt is large scale, tending to be of a zonal nature that should be handled by our model resolution. Freshwater injection onto the North Atlantic and Southern Oceans causes increase of sea level pressure at middle latitudes and decrease at polar latitudes (Figs. 13, S11). These pressure changes have implications for the strength of prevailing winds and for severe weather.

The robust increase of high pressure in the North Atlantic strengthens prevailing northeasterly winds blowing onto the Bahamas (Fig. 13). The Eemian-age chevron beach structures with consistent southwesterly direction throughout windward shores in the Bahamas (Sect. 2.2), with wave runup deposits at elevations as much as 20–40 m above today's sea level and reaching as far as a few kilometers inland, must have been formed by massive storms in the direction of the prevailing winds. Consistent increase of wind speed in the appropriate direction would contribute to creation of long wavelength, deep ocean waves that can scour the ocean floor as they reach the shallow near-shore region. The most extreme events probably required the combined effect of these increased prevailing winds and tropical storms, the latter nurtured by the unusually warm tropical sea surface temperatures in the late Eemian and guided by the strong prevailing winds. On theoretical grounds, it is known that the higher low

latitude sea surface temperatures of the late Eemian (Cortijo et al., 1999) would favor more powerful tropical storms (Emanuel, 1987). The zonal temperature gradient, warmer tropics and cooler high latitudes, was enhanced by low obliquity of Earth's spin axis in the late Eemian. Empirical evidence for intense Eemian storms includes standing forests of 8–10 m trees that were rapidly buried in shelf sand and preserved on Bermuda at elevations several meters above sea level (Hearty and Olson, 2011), as well as other evidence discussed in Sect. 2.2. The late Eemian is typically associated with a massive flux of oolitic shelf sediments mobilized in the offshore shelf environment and further transported by intense winds into enormous land-based dunes that dominate a majority of modern landscapes of the Bahamas archipelago (Hearty and Neumann, 2001).

Shutdown or substantial slowdown of the AMOC, besides possibly contributing to extreme end-Eemian events, will cause a more general increase of severe weather. This is shown by the change of zonal mean temperature and eddy kinetic energy in our simulations with and without ice melt (Fig. 26). Without ice melt, surface warming is largest in the Arctic (Fig. 26, left), resulting in a decrease of lower tropospheric eddy energy. However, the surface cooling from ice melt increases surface and lower tropospheric temperature gradients, and in stark contrast to the case without ice melt, there is a large increase of mid-latitude eddy energy throughout the midlatitude troposphere. The increase of zonal-mean midlatitude baroclinicity that we find (Fig. 26) is in agreement with the localized, N. Atlantic-centered increases in baroclinicity found in the higher resolution simulations of Jackson et al. (2015) and Brayshaw et al. (2009).

Increased baroclinicity produced by a stronger temperature gradient provides energy for more severe weather events. Many of the most memorable and devastating storms in eastern North America and western Europe, popularly known as superstorms, have been winter cyclonic storms, though sometimes occurring in late fall or early spring, that generate near-hurricane force winds and often large amounts of snowfall (Chapter 11, Hansen, 2009). Continued warming of low latitude oceans in coming decades will provide more water vapor to strengthen such storms. If this tropical warming is com-

bined with a cooler North Atlantic Ocean from AMOC slowdown and an increase in midlatitude eddy energy (Fig. 26), we can anticipate more severe baroclinic storms. Increased high pressure due to cooler high latitude ocean (Fig. 13) can make blocking situations more extreme, with a steeper pressure gradient between the storm's low pressure center and the blocking high, thus driving stronger North Atlantic storms.

Large freshwater injection on the North Atlantic Ocean has a different impact on winds than freshwater injection on the Southern Ocean (Fig. 13). In the Southern Ocean the increased meridional temperature gradient increases the strength of the westerlies in all seasons at all longitudes. In the North Atlantic Ocean the increase of sea level pressure in the winter slows the westerlies (Fig. 13). Thus instead of a strong zonal wind that keeps cold polar air locked in the Arctic, there is a tendency for more cold air outbreaks to middle latitudes.

7 Modern data

7.1 Southern Ocean

The Southern Ocean, as the gateway to the global deep ocean, has exerted a powerful control over glacial/interglacial climate. However, the Southern Ocean's control over the Antarctic ice sheet, and thus global sea level, will be of greater concern to humanity.

Our model, due to moderately excessive mixing, may be less sensitive to freshwater forcing than the real world. Yet the model (Fig. 27a) indicates that a slowing of Antarctic Bottom Water Formation should already be underway, a conclusion consistent with transient tracer observations in the Weddell Sea by Huhn et al. (2013), which reveal a 15–21 % reduction in the ventilation of Weddell Sea Bottom Water and Weddell Sea Deep Water over the period 1984–2008.

The Southern Ocean has significant control on release of ocean heat to space. In an extreme case, polynyas form in the dead of Antarctic winter, as upwelling warm water melts the sea ice and raises the air temperature by tens of degrees, increasing

thermal radiation to space, thus serving as a valve that releases ocean heat. Today, as surface meltwater stabilizes the vertical water column, that valve is being partially closed. de Lavergne et al. (2014) relate the absence of large open ocean polynyas in recent decades to surface freshening.

Release of heat to the atmosphere and space, which occurs without the need for large open ocean polynyas, is slowed by increasing sea ice cover in response to increasing ice shelf melt (Bintanja et al., 2013). Schmidtko et al. (2014) and Roemmich et al. (2015) document changes in the Southern Ocean in recent decades, especially warming of Circumpolar Deep Water (CDW), which they and others (Jacobs et al., 2011; Rignot et al., 2013) note is the likely cause of increased ice shelf melt. Observations of ocean surface freshening and freshening of the water column (Rintoul, 2007; Jacobs and Giulivi, 2010) and deep ocean warming (Johnson et al., 2007; Purkey and Johnson, 2013) leave little doubt that these processes are occurring.

Loss of ice shelves that buttress the ice sheets potentially can lead to large sea level rise (Mercer, 1978). The ocean depths with largest warming in response to surface freshening (Fig. 16) encompass ice shelf grounding lines that exert the strongest restraining force (Jenkins and Doake, 1991). The impact of warming CDW varies among ice shelves because of unique geometries and proximity to the CDW current, but eventually a warming ocean will likely affect them all. As ice shelves weaken and ice sheet discharge increases the process is self-amplifying via the increasing freshwater discharge.

Weber et al. (2014) used ocean cores near Antarctica to study the deglacial evolution of the Antarctic ice sheet following the last glacial maximum. They identified eight episodes of large iceberg flux, with the largest flux occurring ~14 600 years ago, providing evidence of an Antarctic contribution to Meltwater Pulse 1A, when sea level rose an average of 3–5 m century^{-1} for a few centuries (Fairbanks, 1989). Ice sheets today may not have as much vulnerable ice as they had during the ice age. On the other hand, CO_2 and the global climate forcing are increasing much more rapidly today, and heat is being pumped into the ocean at a high rate via the resulting positive (incoming)

planetary energy imbalance (Hansen et al., 2011; Roemmich et al., 2015) providing ample energy to spur increasing ice melt.

7.2 Surface change today

Ocean surface cooling near Antarctica is emerging now (Fig. 28) and is large by mid-century (Fig. 20) in our simulations. The modeled sea ice increase is delayed relative to observations (Fig. 27b) for reasons noted below. However, freshwater effects already dominate over direct effects of O_3 and other GHGs. D. Thompson et al. (2011) suggested that O_3 depletion may account for Antarctic sea ice growth, but Sigmond and Fyfe (2014) found that all CMIP5 models yield decreasing sea ice in response to observed changes of O_3 and other GHGs. Ferreira et al. (2015) show that O_3 depletion yields a short time scale sea ice increase that is soon overtaken by warming and sea ice decrease with realistic GHG forcing. We conclude that these models are missing the dominant driver of change on the Southern Ocean: freshwater input.

Delay of our modeled sea ice increase relative to observations is probably related to difficulty in maintaining vertical stratification (Fig. S18), which in turn is a result of excess small scale mixing from a large background diapycnal diffusivity ($0.3\,cm^2\,s^{-1}$) used to damp numerical noise, and the noise itself. Also sea ice increase occurred earlier in our experiments with freshwater spread over a broad area rather than being placed only in coastal gridboxes. In the real world half of the freshwater is calving (icebergs) that float some distance before melting, which may increase the effectiveness of the freshwater flux.

Depoorter et al. (2012) show that the proportion of calving varies strongly with location (see their Fig. 1). The Weddell and Ross Sea regions have large freshwater flux that is mainly icebergs. In contrast, the large Amundsen- Bellingshausen freshwater flux is mainly basal melt. This distinctive spatial variation may help account for observed sea ice increasing in the Weddell and Ross Seas, while decreasing in the Amundsen and Bellingshausen Seas. Note also that the Weddell Sea and Ross Sea sectors are respectively the regions where the EDML and TALDICE Antarctic ice cores

are suggestive of expanding sea ice (Masson-Delmotte et al., 2011) at end-Eemian time.

Observations and our model concur in showing a “global warming hole” near the southern tip of Greenland. Drijfhout et al. (2012) find this feature in most models and conclude that it is a precursor of a weakening AMOC. Freshwater injection in our model makes this feature stronger. We note that this feature creates a blocking situation (Fig. 13) that may have consequences such as directing winter cold air outbreaks southward in Eastern North America. This and possible influence on weather patterns in late spring that initiate melt season conditions should be investigated with models that include the most realistic distribution of Greenland freshwater input (e.g., Fig. 1 of Velicogna et al., 2014) as well as melt from ice shelves and small ice caps.

7.3 Ice sheet mass loss and sea level rise

The fundamental question we raise is whether ice sheet melt in response to rapid global warming will be nonlinear and better characterized by a doubling time for its rate of change or whether more linear processes dominate. Hansen (2005, 2007) argued on heuristic grounds that ice sheet disintegration is likely to be nonlinear if climate forcings continue to grow, and that sea level rise of several meters is possible on a time scale of the order of a century. Given current ice sheet melt rates, a 20 year doubling rate produces multi-meter sea level rise in a century, while 10 and 40 year doubling times require 50 and 200 years, respectively.

The IPCC (2013) report increased estimates of sea level rise compared to prior IPCC reports, but scenarios they discuss are close to linear responses to the assumed rising climate forcing. The most extreme climate forcing (RCP8.5, 936 ppm CO_2 in 2100 and GHG forcing $8.5\,W\,m^{-2}$) is estimated to produce 0.74 m sea level rise in 2100 relative to the 1986–2005 mean sea level, with the “likely” range of uncertainty 0.52–0.98 m. IPCC (2013) also discusses semi-empirical estimates of sea level rise, which yield ~0.7–1.5 m for the RCP8.5 scenario, but preference is given to the model-based estimate of 0.52–0.98 m.

Empirical analyses are needed if we doubt the realism of ice sheet models, but semi-empirical analyses lumping multiple processes together may yield a result that is too linear. Sea level rises as a warming ocean expands, as water storage on continents changes (e.g., in aquifers and behind dams), and as glaciers, small ice caps, and the Greenland and Antarctic ice sheets melt. We must isolate the ice sheet contribution, because only the ice sheets threaten multi-meter sea level rise.

Hay et al. (2015) reanalyzed tide-gauge data for 1901–1990 in a probabilistic framework, including isostatic adjustment at each station, finding global sea level rise $1.2 \pm 0.2\,\mathrm{mm\,yr^{-1}}$. Prior tide gauge analyses of 1.6–$1.9\,\mathrm{mm\,yr^{-1}}$ were inconsistent with estimates for each process, which did not add up to such a large value (IPCC, 2013). The reduced 20th century sea level rise alters perceptions of near-linear sea level rise (Fig. 13.3, IPCC, 2013). For example, Fig. 29 compares satellite altimetry data for 1993-2015 with 20th century sea level change, the latter obtained by multiplying a tide gauge analysis (Church and White, 2011) by the factor (0.78) required to yield sea level rise $1.2\,\mathrm{mm\,yr^{-1}}$ for 1901–1990. Different tide gauge analyses could alter the shape of this curve, but the trend toward earlier times must be toward zero due to near-constancy of millennial sea level (IPCC, 2013).

Figure 29 reveals an accelerating sea level rise, but it includes the effect of all processes affecting sea level and thus may understate the growth rate for ice sheet melt. Recent analysis of satellite gravity measurements (Velicogna et al., 2014) finds Greenland's mass loss in 2003–2013 to be $280 \pm 58\,\mathrm{Gt\,yr^{-1}}$,[3] with mass loss accelerating by $25.4 \pm 1.2\,\mathrm{Gt\,yr^{-2}}$, and Antarctic mass loss $67 \pm 44\,\mathrm{Gt\,yr^{-1}}$ accelerating by $11 \pm 4\,\mathrm{Gt\,yr^{-2}}$ (Fig. S20). Their analysis, which is the source of the quantitative mass

[3]For comparison, our assumed freshwater injection of $360\,\mathrm{Gt\,yr^{-1}}$ in 2011 with 10 year doubling yields an average mass loss $292\,\mathrm{Gt\,yr^{-1}}$ for 2003–2013. Further, Velicogna et al. (2014) find an ice mass loss of $74 \pm 7\,\mathrm{Gt\,yr^{-1}}$ from nearby Canadian glaciers and ice caps with acceleration $10 \pm 2\,\mathrm{Gt\,yr^{-2}}$, and there is an unknown freshwater input from melting ice shelves. Thus our assumed Northern Hemisphere meltwater was conservative.

changes in the remainder of this section, is especially useful because it breaks down the mass changes on Greenland and Antarctica into several regions.

Reliability of the inferred mass loss in 2003–2013 is supported by comparison to surface mass balance studies in regions with little contribution from ice dynamics (Velicogna et al., 2014). Mass loss accelerations over 1992–2011 obtained via the mass budget method (Rignot et al., 2011) for Greenland ($21.9 \pm 1\,\mathrm{Gt\,yr^{-2}}$) and Antarctica ($14.5 \pm 2\,\mathrm{Gt\,yr^{-2}}$) are similar to results from gravity analysis for 2003–2013. A third approach, based on satellite radar altimetry, is consistent with the other two for mass loss from Greenland and West Antarctica (Shepherd et al., 2012), including the Amundsen Sea sector, which is the dominant contributor to Antarctic ice mass loss (Sutterley et al., 2014). Differences among techniques exist in East Antarctica, but mass changes there are small (Shepherd et al., 2012).

Mass loss acceleration for Greenland implies a doubling time of order 10 years, but this high rate may not continue. Greenland mass loss in 2003–2013 was affected by a tendency in 2007–2012 for summer high pressure over Greenland that contributed to melt acceleration (Fettweis, 2013; Bellflamme et al., 2015), especially in 2012 (Hanna et al., 2013). Extreme 2012 melt was associated an "atmospheric river" of warm moist air (Neff et al., 2014), a rare meteorological situation not representative of near-term expectations. Yet extreme events are a combination of slow climate change and infrequent weather patterns, and additional and more summer extreme events can be anticipated if global warming continues (Hansen et al., 2012).

The Antarctic situation, in contrast, is more threatening than suggested by continental mass loss. Net mass loss combines mass loss via ice streams and regions of net snow accumulation. Queen Maud Land is gaining $63 \pm 6\,\mathrm{Gt\,yr^{-1}}$, accelerating $15 \pm 1\,\mathrm{Gt\,yr^{-2}}$, but this mass gain may be temporary. Our simulations with increasing freshwater input indicate that circum-Antarctic cooling and sea ice increase eventually will limit precipitation reaching the continent.

Amundsen Sea glaciers are a gateway to West Antarctic ice with potential for several meters of sea level. Mass loss of the Amundsen Sea sector was $116 \pm 6\,\mathrm{Gt\,yr^{-1}}$ in

2003–2013, growing 13 ± 2 Gt yr^{-2} (Velicogna et al., 2014; Rignot et al., 2014; Sutterley et al., 2014).

Totten glacier in East Antarctica fronts the Aurora Subglacial Basin, which has the potential for ~ 6.7 m of sea level (Greenbaum et al., 2015). Williams et al. (2011) find that warm modified Circumpolar Deep Water is penetrating the continental shelf near Totten beneath colder surface layers. Details of how warmer water reaches the ice shelf are uncertain (Khazendar et al., 2013), but, as in West Antarctica, the inland sloping trough connecting the ocean with the main ice shelf cavity (Greenbaum et al., 2015) makes Totten glacier susceptible to unstable retreat (Goldberg et al., 2009). Cook glacier, further east in East Antarctica, also rests on a submarine inland-sloping bed and fronts ice equivalent to 3–4 m of sea level. The Velicogna et al. (2014) analysis of gravity data for 2003–2013 finds the Totten sector of East Antarctica losing 17 ± 4 Gt yr^{-1}, with the loss accelerating by 4 ± 1 Gt yr^{-2}, and the Victoria/Wilkes sector including Cook glacier losing 16 ± 5 Gt yr^{-1}, with a small deceleration (2 ± 1 Gt yr^{-2}).

Ice mass losses from Greenland, West Antarctica and Totten/Aurora basin in East Antarctica are growing nonlinearly with doubling times of order 10 years. Continued exponential growth at that rate seems unlikely for Greenland, and reduced mass loss in the past two years (Fig. S20) is consistent with a slower growth of the mass loss rate for Greenland. However, if GHGs continue to grow, the amplifying feedbacks in the Southern Ocean, including expanded sea ice and SMOC slowdown likely will continue to grow and facilitate increasing Antarctic mass loss.

7.4 The Anthropocene

The Anthropocene (Crutzen and Stoermer, 2000), the era in which humans have contributed to global climate change, is usually assumed to have begun in the past few centuries. Ruddiman (2003) suggested that it began earlier, with deforestation affecting CO_2 about 8000 years ago. Southern Ocean feedbacks considered in our present paper are relevant to that discussion.

Ruddiman (2003) assumed that 40 ppm of human-made CO_2 was needed to explain a 20 ppm CO_2 increase in the Holocene (Fig. 24c), because CO_2 decreased ~ 20 ppm, on average, during several prior interglacials. Such a large human source should have left an imprint on $\delta^{13}CO_2$ that is not observed in ice core CO_2 (Elsig et al., 2009). Ruddiman (2013) suggests that ^{13}C was taken up in peat formation, but the required peat formation would be large and no persuasive evidence has been presented to support such a dominant role for peat in the glacial carbon cycle.

We suggest that Ruddiman overestimated the anthropogenic CO_2 needed to prevent decline of Antarctic temperature. The CO_2 decline in interglacial periods is a climate feedback: declining Southern Ocean temperature slows the ventilation of the deep ocean, thus sequestering CO_2. Avoidance of the cooling and CO_2 decline requires only human-made CO_2 forcing large enough to counteract the weak natural forcing trend, not the larger feedback-driven CO_2 changes in prior interglacials, because, if the natural forcings are counteracted, the feedback does not occur. The required human-made contribution to atmospheric CO_2 would seem to be at most ~ 20 ppm, but less if human-made CO_2 increased deep ocean ventilation. The smaller requirement on the human source and the low $\delta^{13}C$ content of deep-ocean CO_2 make the Ruddiman hypothesis more plausible, but recent carbon cycle models (Kleinen et al., 2015) have been able to capture CO_2 changes in the Holocene and earlier interglacials without an anthropogenic source.

Even if the Anthropocene began millennia ago, a fundamentally different phase, a Hyper-Anthropocene, was initiated by explosive 20th century growth of fossil fuel use. Human-made climate forcings now overwhelm natural forcings. CO_2, at 400 ppm in 2015, is off the scale in Fig. 24c. CO_2 climate forcing is a reasonable approximation of the net human forcing, because forcing by other GHGs tends to offset negative human forcings, mainly aerosols (IPCC, 2013). Most of the forcing growth occurred in the past several decades, and two-thirds of the 0.9 °C global warming (since 1850) has occurred since 1975 (update of Hansen et al., 2010, available at http://www.columbia.edu/~mhs119/Temperature/).

Our analysis paints a different picture than IPCC (2013) for how this Hyper-Anthropocene phase is likely to proceed if GHG emissions grow at a rate that continues to pump energy at a high rate into the ocean. We conclude that multi-meter sea level rise would become practically unavoidable. Social disruption and economic consequences of such large sea level rise could be devastating. It is not difficult to imagine that conflicts arising from forced migrations and economic collapse might make the planet ungovernable, threatening the fabric of civilization.

This image of our planet with accelerating meltwater includes growing climate chaos and storminess, as meltwater causes cooling around Antarctica and in the North Atlantic while the tropics and subtropics continue to warm. Rising seas and more powerful storms together are especially threatening, providing strong incentive to phase down CO_2 emissions rapidly.

8 Summary implications

Humanity faces near certainty of eventual sea level rise of at least Eemian proportions, 5–9 m, if fossil fuel emissions continue on a business-as-usual course, e.g., IPCC scenario A1B that has CO_2 ~700 ppm in 2100 (Fig. S21). It is unlikely that coastal cities or low-lying areas such as Bangladesh, European lowlands, and large portions of the United States eastern coast and northeast China plains (Fig. S22) could be protected against such large sea level rise.

Rapid large sea level rise may begin sooner than generally assumed. Amplifying feedbacks, including slowdown of SMOC and cooling of the near-Antarctic ocean surface with increasing sea ice, may spur nonlinear growth of Antarctic ice sheet mass loss. Deep submarine valleys in West Antarctica and the Wilkes Basin of East Antarctica, each with access to ice amounting to several meters of sea level, provide gateways to the ocean. If the Southern Ocean forcing (subsurface warming) of the Antarctic ice sheets continues to grow, it likely will become impossible to avoid sea level rise of several meters, with the largest uncertainty being how rapidly it will occur.

The Greenland ice sheet does not have as much ice subject to rapid nonlinear disintegration, so the speed at which it adds to 21st century sea level rise may be limited. However, even a slower Greenland ice sheet response is expected to be faster than carbon cycle or ocean thermal recovery times. Therefore, if climate forcing continues to grow rapidly, amplifying feedbacks will assure large eventual mass loss. Also with present growth of freshwater injection from Greenland, in combination with increasing North Atlantic precipitation, we already may be on the verge of substantial North Atlantic climate disruption.

Storms conjoin with sea level rise to cause the most devastating coastal damage. End-Eemian and projected 21st century conditions are similar in having warm tropics and increased freshwater injection. Our simulations imply increasing storm strengths for such situations, as a stronger temperature gradient caused by ice melt increases baroclinicity and provides energy for more severe weather events. A strengthened Bermuda High in the warm season increases prevailing northeasterlies that can help account for stronger end-Eemian storms. Weakened cold season sea level pressure south of Greenland favors occurrence of atmospheric blocking that can increase wintertime Arctic cold air intrusions into northern midlatitudes.

Effects of freshwater injection and resulting ocean stratification are occurring sooner in the real world than in our model. We suggest that this is an effect of excessive small scale mixing in our model that limits stratification, a problem that may exist in other models (Hansen et al., 2011). We encourage similar simulations with other models, with special attention to the model's ability to maintain realistic stratification and perturbations. This issue may be addressed in our model with increased vertical resolution, more accurate finite differencing method in ocean dynamics that reduces noise, and use of a smaller background diffusivity.

There are many other practical impacts of continued high fossil fuel emissions via climate change and ocean acidification, including irreplaceable loss of many species, as reviewed elsewhere (IPCC, 2013, 2014; Hansen et al., 2013a). However, sea level rise sets the lowest limit on allowable human-made climate forcing and CO_2, because of the

extreme sensitivity of sea level to ocean warming and the devastating economic and humanitarian impacts of a multi-meter sea level rise. Ice sheet response time is shorter than the time for natural geologic processes to remove CO_2 from the climate system, so there is no morally defensible excuse to delay phase-out of fossil fuel emissions as rapidly as possible.

We conclude that the 2 °C global warming "guardrail", affirmed in the Copenhagen Accord (2009), does not provide safety, as such warming would likely yield sea level rise of several meters along with numerous other severely disruptive consequences for human society and ecosystems. The Eemian, less than 2 °C warmer than pre-industrial Earth, itself provides a clear indication of the danger, even though the orbital drive for Eemian warming differed from today's human-made climate forcing. Ongoing changes in the Southern Ocean, while global warming is less than 1 °C, provide a strong warning, as observed changes tend to confirm the mechanisms amplifying change. Predicted effects, such as cooling of the surface ocean around Antarctica, are occurring even faster than modeled.

Our finding of global cooling from ice melt calls into question whether global temperature is the most fundamental metric for global climate in the 21st century. The first order requirement to stabilize climate is to remove Earth's energy imbalance, which is now about $+0.6\,\mathrm{W\,m^{-2}}$, more energy coming in than going out. If other forcings are unchanged, removing this imbalance requires reducing atmospheric CO_2 from ~400 to ~350 ppm (Hansen et al., 2008, 2013a).

The message that the climate science delivers to policymakers, instead of defining a safe "guardrail", is that fossil fuel CO_2 emissions must be reduced as rapidly as practical. Hansen et al. (2013a) conclude that this implies a need for a rising carbon fee or tax, an approach that has the potential to be near-global, as opposed to national caps or goals for emission reductions. Although a carbon fee is the sine qua non for phasing out emissions, the urgency of slowing emissions also implies other needs including widespread technical cooperation in clean energy technologies (Hansen et al., 2013a).

The task of achieving a reduction of atmospheric CO_2 is formidable, but not impossible. Rapid transition to abundant affordable carbon-free electricity is the core requirement, as that would also permit production of net-zero-carbon liquid fuels from electricity. The rate at which CO_2 emissions must be reduced is about $6\,\%\,\mathrm{yr^{-1}}$ to reach 350 ppm atmospheric CO_2 by about 2100, under the assumption that improved agricultural and forestry practices could sequester 100 GtC (Hansen et al., 2013a). The amount of CO_2 fossil fuel emissions taken up by the ocean, soil and biosphere has continued to increase (Fig. S23), thus providing hope that it may be possible to sequester more than 100 GtC. Improved understanding of the carbon cycle and non-CO_2 forcings are needed, but it is clear that the essential requirement is to begin to phase down fossil fuel CO_2 emissions rapidly. It is also clear that continued high emissions are likely to lock-in continued global energy imbalance, ocean warming, ice sheet disintegration, and large sea level rise, which young people and future generations would not be able to avoid. Given the inertia of the climate and energy systems, and the grave threat posed by continued high emissions, the matter is urgent and calls for emergency cooperation among nations.

The Supplement related to this article is available online at doi:10.5194/acpd-15-20059-2015-supplement.

Acknowledgements. Completion of this study was made possible by a generous gift from The Durst Family to the Climate Science, Awareness and Solutions program at the Columbia University Earth Institute. That program was initiated in 2013 primarily via support from the Grantham Foundation for Protection of the Environment, Jim and Krisann Miller, and Gerry Lenfest and sustained via their continuing support. Other substantial support has been provided by the Flora Family Foundation, Dennis Pence, the Skoll Global Threats Fund, Alexander Totic and Hugh Perrine. We thank Anders Carlson, Elsa Cortijo, Nil Irvali, Kurt Lambeck, Scott Lehman, and Ulysses Ninnemann for their kind provision of data and related information. Support for climate simulations was provided by the NASA High-End Computing (HEC) Program through the NASA Center for Climate Simulation (NCCS) at Goddard Space Flight Center.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

References

Abdalati, W., Krabill, W., Frederick, E., Manizade, S., Martin, C., Sonntag, J., Swift, R., Thomas, R., Yungel, J., and Koerner, R.: Elevation changes of ice caps in the Canadian Arctic Archipelago, J. Geophy. Res., 109, F04007, doi:10.1029/2003JF000045, 2004.

Adkins, J. F., Boyle, E. A., Keigwin, L., and Cortijo, E.: Variability of the North Atlantic thermohaline circulation during the last interglacial period, Nature, 390, 154–156, 1997.

Ahn, J., Brrok, E. J., Schmittner, A., and Kreutz, K.: Abrupt change in atmospheric CO_2 during the last ice age, Geophys. Res. Lett., 39, L18711, doi:10.1029/2012GL053018, 2012.

Alley, R. B., Dupont, T. K., Parizek, B. R., Anandakrishnan, S., Lawson, D. E., Larson, G. J., and Evenson, E. B.: Outburst flooding and the initiation of ice-strem surges in response to climatic cooling: a hypothesis, Geomorphology, 75, 76–89, 2006.

Alvarez-Solas, J., Charbit, S., Ritz, C., Paillard, D., Ramstein, G., and Dumas, C.: Links between ocean temperature and iceberg discharge during Heinrich events, Nature Geosci., 3, 122–126, 2010.

Álvarez-Solas, J., Montoya, M., Ritz, C., Ramstein, G., Charbit, S., Dumas, C., Nisancioglu, K., Dokken, T., and Ganopolski, A.: Heinrich event 1: an example of dynamical ice-sheet reaction to oceanic changes, Clim. Past, 7, 1297–1306, doi:10.5194/cp-7-1297-2011, 2011.

Alvarez-Solas, J., Robinson, A., Montoya, M., and Ritz, C.: Iceberg discharges of the last glacial period driven by oceanic circulation changes, Proc. Natl. Acad. Sci. USA, 110, 16350–16354, 2013.

Anderson, R. F., Ali, S., Bradtmiller, L. I., Nielsen, S. H. H., Fleisher, M., Andersen, B., and Burckle, L.: Wind-driven upwelling in the Southern Ocean and the deglacial rise in atmospheric CO_2, Science, 323, 1443–1448, 2009.

Antonov, J. I., Seidov, D., Boyer, T. P., Locarnini, R. A., Mishonov, A. V., Garcia, H. E., Baranova, O. K., Zweng, M. M., and Johnson, D. R.: World Ocean Atlas 2009, Vol. 2: Salinity, NOAA Atlas NESDIS 68, edited by: Levitus, S., U.S. Government Printing Office, Washington, DC, 184 pp., 2010.

Archer, D.: Fate of fossil fuel CO_2 in geologic time, J. Geophys. Res., 110, C09505, doi:10.1029/2004JC002625, 2005.

Archer, D., Winguth, A., Lea, D., and Mahowald, N.: What caused the glacial/interglacial atmospheric CO_2 cycles?, Rev. Geophys., 38, 159–189, 2000.

Bahr, D. B., Dyurgerov, M., and Meier, M. F.: Sea-level rise from glaciers and ice caps: a lower bound, Geophys. Res. Lett., 36, L03501, doi:10.1029/2008GL036309, 2009.

Bain, R. J. and Kindler, P.: Irregular fenestrae in Bahamian eolianites: a rainstorm-induced origin, J. Sedimen. Petrology, A64, 140–146, 1994.

Bard, E., Fairbanks, R. G., and Hamelin, B.: How accurate are the U-Th ages obtained by mass spectrometry on coral terraces?, in: Start of a Glacial, edited by: Kukla, G. and Went, E., Springer-Verlag, Berlin, 15–21, 1992.

Baringer, M. O., Johns, W. E., McCarthy, G., Willis, J., Garzoli, S., Lankhortst, M., Meinen, C. S., Send, U., Hobbs, W. R., Cunningham, S. A., Rayner, D., Smeed, D. A., Kanzow, T. O., Heimbach, P., Frajka-Williams, E., Macdonald, A., Dong, S., and Marotzke, J.: Meridional overturning circulation and heat transport observations in the Atlantic Ocean, in Stae of the Climate in 2012, Bull. Amer. Meteorol. Soc., 94, S65–S68, 2013.

Barletta, V. R., Sørensen, L. S., and Forsberg, R.: Scatter of mass changes estimates at basin scale for Greenland and Antarctica, The Cryosphere, 7, 1411–1432, doi:10.5194/tc-7-1411-2013, 2013.

Barreiro, M., Fedorov, A., Pacanowski, R., and Philander, S. G.: Abrupt climate changes: how freshening of the northern Atlantic affects the thermohaline and wind-driven oceanic circulations, Ann. Rev. Earth Planet. Sci., 36, 33–58, 2008.

Bauch, D., Holemann, J. A., Dmitrenko, I. A., Janout, M. A., Nikulina, A., Kirillov, S. A., Krumpen, T., Kassens, H., and Timokhov, L.: Impact of Siberian coastal polynyas on shelf-derived Arctic Ocean halocline waters, J. Geophys. Res., 117, C00G12, doi:10.1029/2011JC007282, 2012.

Bauch, H. A. and Erlenkeuser, H.: A “critical” climatic evaluation of the last interglacial (MIS 5e) records from the Norwegian Sea, Polar Res., 27, 135–151, 2008.

Bauch, H. A. and Kandiano, E. S.: Evidence for early warming and cooling in North Atlantic surface waters during the last interglacial, Paleoceanography, 22, PA1201, doi:10.1029/2005PA001252, 2007.

Bauch, H. A., Kandiano, E. S., and Helmke, J. P.: Contrasting ocean changes between the subpolar and polar North Atlantic during the past 135 ka, Geophys. Res. Lett., 39, L11604, doi:10.1029/2012GL051800, 2012.

Bazin, L., Landais, A., Lemieux-Dudon, B., Toyé Mahamadou Kele, H., Veres, D., Parrenin, F., Martinerie, P., Ritz, C., Capron, E., Lipenkov, V., Loutre, M.-F., Raynaud, D., Vinther, B., Svensson, A., Rasmussen, S. O., Severi, M., Blunier, T., Leuenberger, M., Fischer,

H., Masson-Delmotte, V., Chappellaz, J., and Wolff, E.: An optimized multi-proxy, multi-site Antarctic ice and gas orbital chronology (AICC2012): 120–800 ka, Clim. Past, 9, 1715–1731, doi:10.5194/cp-9-1715-2013, 2013.

Belleflamme, A., Fettweis, X., and Erpicum, M.: Recent summer Arctic atmospheric circulation anomalies in a historical perspective, The Cryosphere, 9, 53–64, doi:10.5194/tc-9-53-2015, 2015.

Berger, A. L.: Long-term variations of caloric insolation resulting from the Earth's orbital elements, Quaternary Res., 9, 139–167, 1978.

Bintanja, R., van Oldenborgh, G. J., Drijfhout, S. S., Wouters, B., and Katsman, C. A.: Important role for ocean warming and increased ice-shelf melt in Antarctic sea-ice expansion, Nature Geosci., 6, 376–379, 2013.

Blanchon, P., Eisenhauer, A., Fietzke, J., and Liebetrau, V.: Rapid sea-level rise and reef backstepping at the close of the last interglacial highstand, Nature, 458, 881–885, 2009.

Box, J. E., Fettweis, X., Stroeve, J. C., Tedesco, M., Hall, D. K., and Steffen, K.: Greenland ice sheet albedo feedback: thermodynamics and atmospheric drivers, The Cryosphere, 6, 821–839, doi:10.5194/tc-6-821-2012, 2012.

Boyle, E. A.: Vertical oceanic nutrient fractionation and glacial/interglacial CO_2 cycles, Nature, 331, 55–56, 1988.

Brauer, A., Allen, J. R. M., Minigram, J., Dulski, P., Wulf, S., and Huntley, B.: Evidence for last interglacial chronology and environmental change from Southern Europe, Proc. Natl. Acad. Sci. USA, 104, 450–455, 2007.

Brayshaw, D. J., Woollings, T., and Vellinga, M.: Tropical and extratropical responses of the North Atlantic atmospheric circulation to a sustained weakening of the MOC, J. Climate, 22, 3146–3155, 2009.

Broecker, W. S.: Terminations, in Milankovitch and Climate, Part 2, edited by: Berger, A. L., Imbrie, J. Hays, J., Kukla, G., and Salzman, B., 687–698, D. Reidel, Norwell, MA, 1984.

Broecker, W. S.: Salinity history of the northern Atlantic during the last deglaciation, Paleoceanography, 5, 459–467, 1990.

Broecker, W. S.: Paleocean circulation during the last deglaciation: A bipolar seesaw?, Paleoceanography, 13, 119–121, 1998.

Broecker, W. S.: Abrupt climate change: causal constraints provided by the paleoclimate record, Earth-Sci. Rev., 51, 137–154, 2000.

Broecker, W. S.: Massive iceberg discharges as triggers for global climate change, Nature, 372, 421–424, 2002.

Broecker, W. S., Bond, G., Klas, M., Bonani, G., and Wolfli, W.: A salt oscillator in the glacial Atlantic? 1. The concept, Paleoceanography, 5, 469–477, 1990.

Buizert, C., Gkinis, V., Severinghaus, J. P., He, F., Lecavalier, B. S., Kindler, P., Leuenberger, M., Carlson, A. E., Vinther, B., Masson-Delmotte, V., White, J. W. C., Liu, Z., Otto-Bliesner, B., and Brook, E. J.: Greenland temperature response to climate forcing during the last deglaciation, Science, 345, 1177–1180, 2014.

Burke, A. and Robinson, L. F.: The Southern Ocean's role in carbon exchange during the last deglaciation, Science, 335, 557–561, 2012.

Capron, E., Landais, A., Lemieux-Dudon, B., Schilt, A., Masson-Delmotte, V., Buiron, D., Chappellaz, J., Dahl-Jensen, D., Johnsen, S., Leuenberger, M., Loulergue, L., and Oerter, H.: Synchronizing EDML and NorthGRIP ice cores using $\delta^{18}O$ of atmospheric oxygen ($\delta^{18}O_{atm}$) and CH_4 measurements over MIS5 (80–123 kyr), Quaternary Sci. Rev., 29, 222–234, 2010.

Carlson, A. E., Stoner, J. S., Donnelly, J. P., and Hillaire-Marcel, C.: Response of the southern Greenland ice sheet during the last two deglaciations, Geology, 36, 359–362, 2008.

Carton, J. A. and Hakkinen, S.: Introduction to: Atlantic Meridional Overturning Circulation (AMOC), Deep-Sea Res. Pt. II, 58, 1741–1743, 2011.

Chapman, M. R. and Shackleton, N. J.: Global ice-volume fluctuations, North Atlantic ice-rafting events, and deep-ocean circulation changes between 130 and 70 ka, Geology, 27, 795–798, 1999.

Chappell, J.: Sea level changes forced ice breakouts in the Last Glacial cycle: new results from coral terraces, Quaternary Sci. Rev., 21, 1229–1240, 2002.

Chen, J. H., Curran, H. A. White, B., and Wasserburg, G. J.: Precise chronology of the last interglacial period: ^{234}U-^{230}Th data from fossil coral reefs in the Bahamas, Geol. Soc. Amer. Bull, 103, 82–97, 1991.

Cheng, W., Chiang, J. C. H., and Zhang, D.: Atlantic Meridional Overturning Circulation (AMOC) in CMIP5 models: RCP and historical simulations, J. Climate, 26, 7187–7198, 2013.

Church, J. A. and White, N. J.: Sea level rise from the late 19th to the early 21st century, Surv. Geophys., 32, 585–602, 2011.

Clarke, G. K. C., Leverington, D. W., Teller, J. T., and Dyke, A. S.: Paleohydraulics of the last outburst flood from glacial Lake Agassiz and the 8200 B.P. cold event, Quaternay Sci. Rev., 23, 389–407, 2004.

Copenhagen Accord: United Nations Framework Convention on Climate Change, Draft decision – /CP.15 FCCC/CP/2009/L.7, 18 December 2009.

Cortijo, E., Lehman, S., Keigwin, L., Chapman, M., Paillard, D., and Labeyrie, L.: Changes in meridional temperature and salinity gradients in the North Atlantic Ocean (30°–72° N) during the last interglacial period, Paleoceanography, 14, 23–33, 1999.

Crowley, T. J.: North Atlantic deep water cools the Southern Hemisphere, Paleoceanography, 7, 489–497, 1992.

Crutzen, P. J. and Stoermer, F. F.: The "Anthropocene", IGBP Newsl., 41, 12–14, 2000.

Curran, H. A., Wilson, M. A., and Mylroie, J. E.: Fossil palm frond and tree trunk molds: occurrence and implications for interpretation of Bahamian Quaternary carbonate eolianites, in: Proc. 13th Symposium on the Geology of the Bahamas and Other Carbonate Regions: Gerace Reserch Center, edited by: Park, L. E. and Freile, D., San Salvador, Bahamas, 183–195, 2008.

Cutler, K. B., Edwards, R. L., Taylor, F. W., Cheng, H., Adkins, J., Gallup, C. D., Cutler, P. M., Burr, G. S., and Bloom, A. L.: Rapid sea-level fall and deep-ocean temperature change since the last interglacial period, Earth Planet. Sci. Lett., 206, 253–271, 2003.

Dansgaard, W., Johnsen, S. J., Clausen, H. B., Dahl-Jensen, D., Gudestrup, N. S., Hammer, C. U., Hvidberg, C. S., Steffensen, J. P., Sveinbjornsdottir, A. E., Jouzel, J., and Bond, G.: Evidence for general instability of past climate from a 250-kyr ice-core record, Nature, 364, 218–220, 1993.

de Boer, B., Van de Wal, R. S. W., Bintanja, R., Lourens, L. J., and Tuenter, E.: Cenozoic global ice-volume and temperature simulations with 1-D ice-sheet models forced by benthic δ^{18}O records, Ann. Glaciol., 51, 23–33, 2010.

De Boyer Montegut, C., Madec, G., Fisher, A. S., Lazar, A., and Iudicone, D.: Mixed layer depth over the global ocean: an examination of profile data and a profile-based climatology, J. Geophys. Res., 109, C12003, doi:10.1029/2004JC002378, 2004.

De Lavergne, C., Palter, J. B., Galbraith, E. D., Bernardello, R., and Marinov, I.: Cessation of deep convection in the open Southern Ocean under anthropogenic climate change, Nature Clim. Change, 4, 278–282, doi:10.1038/nclimate2132, 2014.

Deporter, M. A., Bamber, J. L., Griggs, J. A., Lenaerts, J. T. M., Ligtenberg, S. R. M., van den Broeke, M. R., and Moholdt, G.: Calving fluxes and basal melt rates of Antarctic ice shelves, Nature, 502, 89–92, 2013.

Deschamps, P., Durand, N., Bard, E., Hamelin, B., Camoin, G., Thomas, A. L., Henderson, G. M., Okuno, J., and Yokoyama, Y.: Ice-sheet collapse and sea-level rise at the Bolling warming 14,600 years ago, Nature, 483, 559–564, 2012.

DeVries, T. and Primeau, F.: Dynamically and observationally constrained estimates of water-mass distributions and ages in the global ocean, J. Phys. Oceanogr., 41, 2381–2401, 2011.

Ditlevsen, P. D., Andersen, K. K., and Svensson, A.: The DO-climate events are probably noise induced: statistical investigation of the claimed 1470 years cycle, Clim. Past, 3, 129–134, doi:10.5194/cp-3-129-2007, 2007.

Drijfhout, S., Oldenborgh, G. J., and Cimatoribus, A.: Is a decline of AMOC causing the warming hole above the North Atlantic in observed and modeled warming patterns?, J. Climate, 25, 8373–8379, 2012.

Duplessy, J. C., Shackleton, N. J., Fairbanks, R. G., Labeyrie, L., Oppo, P., and Kallel, N.: Deep water source variations during the last climatic cycle and their impact on the global deep water circulation, Paleoceanography, 3, 343–360, 1988.

Durack, P. J. and Wijffels, S. E.: Fifty-year trends in global ocean salinities and their relationship to broad-scale warming, J. Climate, 23, 4342–4362, 2010.

Durack, P. J., Wijffels, S. E., and Matear, R. J.: Ocean salinities reveal strong global water cycle intensification during 1950 to 2000, Science, 336, 455–458, 2012.

Dutton, A. and Lambeck, K.: Ice volume and sea level during the last interglacial, Science, 337, 216–219, 2012.

Edwards, R. L., Gallup, C. D., and Cheng, H.: Uranium-series dating of marine and lacustrine carbonates, in: Uranium-series Geochemistry, edited by: Bourdon, B., Henderson, G. M., Lundstrom, C. C., and Turner, S. P., Mineralogical Society of America, Washington, DC, 656 pp., 2003.

Elsig, J., Schmitt, J., Leuenberger, D., Schneider, R., Eyer, M., Leuenberger, M., Joos, F., Fischer, H., and Stocker, T. F.: Stable isotope constraints on Holocene carbon cycle changes from an Antarctic ice core, Nature, 461, 507–510, 2009.

Emanuel, K.: Increasing destructiveness of tropical cyclones over the past 30 years, Nature, 436, 686–688, 2005.

Emanuel, K. A.: The dependence of hurricane intensity on climate, Nature, 326, 483–485, 1987.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

Engelbrecht, A. C. and Sachs, J. P.: Determination of sediment provenance at drift sites using hydrogen isotopes and unsaturation ratios in alkenones, Geochim. Cosmochim. Acta, 69, 4253–4265, 2005.

EPICA Community Members: One-to-one coupling of glacial climate variability in Greenland and Antarctica, Nature, 444, 195–198, 2006.

Fairbanks, R. G.: A 17,000-year glacio-eustatic sea-level record-influence of glacial melting rates on the younger rates on the Younger Dryas event and deep-ocean circulation, Nature, 342, 637–642, 1989.

Ferreira, D., Marshall, J., Bitz, C. M., Solomon, S., and Plumb, A.: Antarctic Ocean and sea ice response to ozone depletion: a two-time-scale problem, J. Climate, 28, 1206–1226, 2015.

Fetterer, F., Knowles, K., Meier, W., and Savoie, M.: Sea Ice index updated daily, National Snow and Ice Data Center, available at: http://dx.doi.org/10.7265/N5QJ7F7W (last access: 10 March 2015), Boulder, CO, USA, 2002.

Fettweis, X., Hanna, E., Lang, C., Belleflamme, A., Erpicum, M., and Gallée, H.: Brief communication "Important role of the mid-tropospheric atmospheric circulation in the recent surface melt increase over the Greenland ice sheet", The Cryosphere, 7, 241–248, doi:10.5194/tc-7-241-2013, 2013.

Fichefet, T., Poncin, C., Goosse, H., Huybrechts, P., Janssens, I., and Le Treut, H.: Implications of changes in freshwater flux from the Greenland ice sheet for the climate of the 21st century, Geophys. Res. Lett., 30, 1911, doi:10.1029/2003GL017826, 2003.

Fischer, H., Schmitt, J., Luthi, D., Stocker, T. F., Tschumi, T., Parekh, P., Joos, F., Kohler, P., Volker, C., Gersonde, R., Barbante, C., Le Floch, M., Raynaud, D., and Wolff, E.: The role of Southern Ocean processes in orbital and millennial CO_2 variations – a synthesis, Quaternary Sci. Rev., 29, 193–205, 2010.

Fischer, H., Schmitt, J., Eggleston, S., Schneider, R., Elsig, J., Joos, F., Leuenberger, Stocker, T. F., Kohler, P., Brovkin, V., and Chappellaz, J.: Ice core-based isotopic constraints on past carbon cycle changes, PAGES, 23, 12–13, 2015.

Fluckiger, J., Knutti, R., and White, J. W. C.: Oceanic processes as potential trigger and amplifying mechanisms for Heinrich events, Paleoceanography, 21, PA2014, doi:10.1029/2005PA001204, 2006.

Fretwell, P., Pritchard, H. D., Vaughan, D. G., Bamber, J. L., Barrand, N. E., Bell, R., Bianchi, C., Bingham, R. G., Blankenship, D. D., Casassa, G., Catania, G., Callens, D., Conway, H., Cook, A. J., Corr, H. F. J., Damaske, D., Damm, V., Ferraccioli, F., Forsberg, R., Fujita, S., Gim, Y.,

Gogineni, P., Griggs, J. A., Hindmarsh, R. C. A., Holmlund, P., Holt, J. W., Jacobel, R. W., Jenkins, A., Jokat, W., Jordan, T., King, E. C., Kohler, J., Krabill, W., Riger-Kusk, M., Langley, K. A., Leitchenkov, G., Leuschen, C., Luyendyk, B. P., Matsuoka, K., Mouginot, J., Nitsche, F. O., Nogi, Y., Nost, O. A., Popov, S. V., Rignot, E., Rippin, D. M., Rivera, A., Roberts, J., Ross, N., Siegert, M. J., Smith, A. M., Steinhage, D., Studinger, M., Sun, B., Tinto, B. K., Welch, B. C., Wilson, D., Young, D. A., Xiangbin, C., and Zirizzotti, A.: Bedmap2: improved ice bed, surface and thickness datasets for Antarctica, The Cryosphere, 7, 375–393, doi:10.5194/tc-7-375-2013, 2013.

Frieler, K., Clark, P. U., He, F., Buizert, C., Reese, R., Ligtenberg, S. R. M., van den Broeke, M. R., Winkelmann, R., and Levermann, A.: Consistent evidence of increasing Antarctic accumulation with warming, Nature Clim. Chan., 5, 348–352, 2015.

Fronval, T. and Jansen, E.: Rapid changes in ocean circulation and heat flux in the Nordic seas during the last interglacial period, Nature, 383, 806–810, 1996.

Galaasen, E. V., Ninnemann, U. S., Irvali, N., Kleiven, H. F., Rosenthal, Y., Kissel, C., and Hodell, D.: Rapid reductions in North Atlantic deep water during the peak of the last interglacial period, Science, 343, 1129–1132, 2014.

Gent, P. R. and McWilliams, J. C.: Isopycnal mixing in ocean circulation models, J. Geophys. Res., 20, 150–155, 1990.

Goldberg, D., Holland, D. M., and Schoof, C.: Grounding line movement and ice shelf buttressing in marine ice sheets, J. Geophys. Res., 114, F04026, doi:10.1029/2008JF001227, 2009.

Govin, A., Michel, E., Labeyrie, Laurent, Waelbroeck, C., Dewilde, F., and Jansen, E.: Evidence for northward expansion of Antarctic Bottom Water mass in the Southern Ocean during the last glacial inception, Paleocenography, 24, PA1202, doi:10.1029/2008PA001603, 2009.

Grant, K. M., Rohling, E. J., Bar-Matthews, M., Ayalon, A., Medina-Elizade, M., Ramsey, C. B., Satow, C., and Roberts, A. P.: Rapid couplings between ice volume and polar temperature over the past 150,000 years, Nature, 491, 744–747, 2012.

Greenbaum, J. S., Blankenship, D. D., Young, D. A., Richter, T. G., Roberts, J. L., Aitken, A. R. A., Legresy, B., Schroeder, D. M., Warner, R. C., van Ommen, T. D., and Siegert, M. J.: Ocean access to a cavity beneath Totten Glacier in East Antarctica, Nat. Geosci., 8, 294–298, doi:10.1038/NGEO2388, 2015.

Gregory, J. M., Dixon, K. W., Stouffer, R. J., Weaver, A. J., Driesschaert, E., Eby, M., Fichefet, T., Hasumi, H., Hu, A., Jungclaus, J. H., Kamenkovich, I. V., Levermann, A., Montoya, M., Murakami, S., Nawrath, S., Oka, A., Sokolov, A. P., and Thorpe, R. B.: A model intercompari-

son of changes in the Atlantic thermohaline circulation in response to increasing atmospheric CO_2 concentration, Geophys. Res. Lett., 32, L12703, doi:10.1029/2005GL023209, 2005.

Guillevic, M., Bazin, L., Landais, A., Kindler, P., Orsi, A., Masson-Delmotte, V., Blunier, T., Buchardt, S. L., Capron, E., Leuenberger, M., Martinerie, P., Prié, F., and Vinther, B. M.: Spatial gradients of temperature, accumulation and δ^{18}O-ice in Greenland over a series of Dansgaard–Oeschger events, Clim. Past, 9, 1029–1051, doi:10.5194/cp-9-1029-2013, 2013.

Guillevic, M., Bazin, L., Landais, A., Stowasser, C., Masson-Delmotte, V., Blunier, T., Eynaud, F., Falourd, S., Michel, E., Minster, B., Popp, T., Prié, F., and Vinther, B. M.: Evidence for a three-phase sequence during Heinrich Stadial 4 using a multiproxy approach based on Greenland ice core records, Clim. Past, 10, 2115–2133, doi:10.5194/cp-10-2115-2014, 2014.

Hanna, E., Jones, J. M., Cappelen, J., Mernild, S. H., Wood, L., Steffen, K., and Huybrechts, P.: The influence of North Atlantic atmospheric and oceanic forcing effects on 1900–2010 Greenland summer climate and ice melt/runoff, Int. J. Climatol., 33, 862–880, 2013.

Hansen, J.: A slippery slope: How much global warming constitutes “dangerous anthropogenic interference”?, Climatic Change, 68, 269–279, 2005.

Hansen, J.: Scientific reticence and sea level rise, Environ. Res. Lett., 2, 024002, doi:10.1088/1748-9326/2/2/024002, 2007.

Hansen, J.: Storms of My Grandchildren, New York, Bloomsbury, 304 pp., 2009.

Hansen, J., Sato, M., Ruedy, R., Lacis, A., and Oinas, V.: Global warming in the twenty-first century: an alternative scenario, Proc. Natl. Acad. Sci. USA, 97, 9875–9880, 2000.

Hansen, J., Sato, M., Ruedy, R., Nazarenko, L., Lacis, A., Schmidt, G. A., Russell, G., Aleinov, I., Bauer, M., Bauer, S. Bell, N., Cairns, B., Canuto, V., Chandler, M., Cheng, Y., Del Genio, A., Faluvegi, G., Fleming, E., Friend, A., Hall, T., Jackman, C., Kelley, M., Kiang, N. Y., Koch, D., Lean, J., Lerner, J., Lo, K., Menon, S., Miller, R. L., Minnis, P., Novakov, T., Oinas, V., Perlwitz, J. P., Perlwitz, J., Rind, D., Romanou, A., Shindell, D., Stone, P., Sun, S., Tausnev, N., Thresher, D., Wielicki, B., Wong, T., Yao, M. and Zhang, S.: Efficacy of climate forcings, J. Geophys. Res., 110, D18104, doi:10.1029/2005JD005776, 2005.

Hansen, J., Sato, M., Ruedy, R., Kharecha, P., Lacis, A., Miller, R., Nazarenko, L., Lo, K., Schmidt, G. A., Russell, G., Aleinov, I., Bauer, S., Baum, E., Cairns, B., Canuto, V., Chandler, M., Cheng, Y., Cohen, A., Del Genio, A., Faluvegi, G., Fleming, E., Friend, A., Hall, T., Jackman, C., Jonas, J., Kelley, M., Kiang, N. Y., Koch, D., Labow, G., Lerner, J., Menon, S., Novakov, T., Oinas, V., Perlwitz, J. P., Perlwitz, J., Rind, D., Romanou, A., Schmunk, R.,

Shindell, D., Stone, P., Sun, S., Streets, D., Tausnev, N., Thresher, D., Unger, N., Yao, M., and Zhang, S.: Climate simulations for 1880–2003 with GISS modelE, Clim. Dynam., 29, 661–696, doi:10.1007/s00382-007-0255-8, 2007a.

Hansen, J., Sato, M., Kharecha, P., Russell, G., Lea, D. W., and Siddall, M.: Climate change and trace gases, Phil. Trans. R. Soc. A, 36, 1925–1954, doi:10.1098/rsta.2007.2052, 2007b.

Hansen, J., Sato, M., Ruedy, R., Kharecha, P., Lacis, A., Miller, R., Nazarenko, L., Lo, K., Schmidt, G. A., Russell, G., Aleinov, I., Bauer, S., Baum, E., Cairns, B., Canuto, V., Chandler, M., Cheng, Y., Cohen, A., Del Genio, A., Faluvegi, G., Fleming, E., Friend, A., Hall, T., Jackman, C., Jonas, J., Kelley, M., Kiang, N. Y., Koch, D., Labow, G., Lerner, J., Menon, S., Novakov, T., Oinas, V., Perlwitz, Ja., Perlwitz, Ju., Rind, D., Romanou, A., Schmunk, R., Shindell, D., Stone, P., Sun, S., Streets, D., Tausnev, N., Thresher, D., Unger, N., Yao, M., and Zhang, S.: Dangerous human-made interference with climate: a GISS modelE study, Atmos. Chem. Phys., 7, 2287–2312, doi:10.5194/acp-7-2287-2007, 2007c.

Hansen, J., Sato, M., Kharecha, P., Beerling, D., Berner, R., Masson-Delmotte, V., Pagani, M., Raymo, M., Royer, D. and Zachos, J.: Target Atmospheric CO_2: Where Should Humanity Aim?, Open Atmos. Sci. J., 2, 217–231, 2008.

Hansen, J., Ruedy, R., Sato, M., and Lo, K.: Global surface temperature change, Rev. Geophys., 48, RG4004, doi:10.1029/2010RG000345, 2010.

Hansen, J., Sato, M., Kharecha, P., and von Schuckmann, K.: Earth’s energy imbalance and implications, Atmos. Chem. Phys., 11, 13421–13449, doi:10.5194/acp-11-13421-2011, 2011.

Hansen, J., Sato, M., and Ruedy, R.: Perception of climate change, Proc. Natl. Acad. Sci., 109, 14726–14727, doi:10.1073/pnas.1205276109, 2012.

Hansen, J., Kharecha, P., Sato, M., Masson-Delmotte, V., Ackerman, F., Beerling, D., Hearty, P. J., Hoegh-Guldberg, O., Hsu, S.-L., Parmesan, C., Rockstrom, J., Rohling, E. J., Sachs, J., Smith, P., Steffen, K., Van Susteren, L., von Schuckmann, K., and Zachos, J. C.: Assessing “dangerous climate change”: Required reduction of carbon emissions to protect young people, future generations and nature, PLOS ONE, 8, e81648, doi:10.1371/journal.pone.0081648, 2013a.

Hansen, J., Sato, M., Russell, G., and Kharecha, P.: Climate sensitivity, sea level and atmospheric CO_2, Phil. Trans. Roy. Soc. A, 371, 20120294, doi:10.1098/rsta.2012.0294, 2013b.

Hansen, J., Kharecha, P. and Sato, M.: Climate forcing growth rates: Doubling down on our Faustian bargain, Environ. Res. Lett., 8, 011006, doi:10.1088/1748-9326/8/1/011006, 2013c.

Hay, C. C., Morrow, E., Kopp, R. E., and Mitrovica, J. X.: Probabilistic reanalysis of twentieth-century sea-level rise, Nature, 517, 481–484, 2015.

Hays, J. D., Imbrie, J., and Shackleton, N. J.: Variations in the Earth's orbit: pacemaker of the ice ages, Science, 194, 1121–1132, 1976.

Hearty, P. J.: Boulder deposits from large waves during the Last Interglaciation on North Eleuthera Island, Bahamas, Quaternary Res., 48, 326–338, 1997.

Hearty, P. J.: The geology of Eleuthera Island, Bahamas: A Rosetta stone of Quaternary stratigraphy and sea-level history, Quaternary Sci. Rev., 17, 333–355, 1998.

Hearty, P. J. and Kindler, P.: New perspectives on Bahamian geology, San Salvador Island, Bahamas, J. Coastal Res., 9, 577–594, 1993.

Hearty, P. J. and Neumann, A. C.: Rapid sea level and climate change at the close of the Last Interglaciation (MIS 5e): evidence from the Bahama Islands, Quaternary Sci. Rev., 20, 1881–1895, 2001.

Hearty, P. J. and Olson, S. L.: Preservation of trace fossils and models of terrestrial biota by intense storms in mid-last interglacial (MIS 5c) dunes on Bermuda, with a model for development of hydrological conduits, Palaios, 26, 394–405, 2011.

Hearty, P. J., Neumann, A. C., and Kaufman, D. S.: Chevron ridges and runup deposits in the Bahamas from storms late in oxygen-isotope substage 5e, Quaternary Res. 50, 309–322, 1998.

Hearty, P. J., Hollin, J. T., Neumann, A. C., O'Leary, M. J., and McCulloch, M.: Global sea-level fluctuations during the Last Interglaciation (MIS 5e), Quaternary Sci. Rev., 26, 2090–2112, 2007.

Heinrich, H.: Origin and consequences of cyclic ice rafting in the northeast Atlantic Ocean during the past 130,000 years, Quaternary Res., 29, 142–152, 1988.

Hemming, S. R.: Heinrich events: massive late Pleistocene detritus layers of the North Atlantic and their global climate imprint, Rev. Geophys., 42, RG1005, doi:10.1029/2003RG000128, 2004.

Heuze, C., Heywood, K. J., Stevens, D. P., and Ridley, J. K.: Southern Ocean bottom water characteristics in CMIP5 models, Geophys. Res. Lett., 40, 1409–1414, doi:10.1002/grl.50287, 2013.

Heuze, C., Heywood, K. J., Stevens, D. P., and Ridley, J. K.: Changes in global ocean bottom properties and volume transports in CMIP5 models under climate change scenarios, J. Climate, 28, 2917–2944, doi:10.1175/JCLI-D-14-00381.1, 2015.

Hu, A., Meehl, G. A., Han, W., and Yin, J.: Transient response of the MOC and climate to potential melting of the Greenland Ice Sheet in the 21st century, Geophys. Res. Lett., 36, L10707, doi:10.1029/2009GL037998, 2009.

Hu, A., Meehl, G. A., Han, W., and Yin, J.: Effect of the potential melting of the Greenland ice sheet on the meridional overturning circulation and global climate in the future, Deep-Sea Res. Pt. II, 58, 1914–1926, 2011.

Huhn, O., Rhein, M., Hoppema, M., and van Heuven, S.: Decline of deep and bottom water ventilation and slowing down of anthropogenic carbon storage in the Weddell Sea, 1984–2011, Deep-Sea Res. Pt. I, 76, 66–84, 2013.

Huybrechts, P., Janssens, I., Poncin, C., and Fichefet, T.: The response of the Greenland ice sheet to climate changes in the 21st century by interactive coupling of an AOGCM with a thermomechanical ice-sheet model, Ann. Glaciol., 35, 409–415, 2002.

Intergovernmental Panel on Climate Change (IPCC): Climate Change 2007: The Physical Science Basis, edited by: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K. B., Tignor, M., and Miller, H. L., Cambridge University Press, 996 pp., 2007.

Intergovernmental Panel on Climate Change (IPCC): Climate Change 2013, edited by: Stocker, T. F., Qin, D., Plattner, G. K., Tignor, M. M. B., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge University Press, available at: http://www.ipcc.ch/report/ar5/wg1/#.UlCweRCvHMM, 1535 pp., 2013.

Intergovernmental Panel on Climate Change (IPCC): Climate Change 2014: Impacts, Adaptation, and Vulnerability, edited by: Field, C., Mach, K., Mastrandrea, M., and Barros, R., Cambridge University Press, 1132 pp., 2014.

Irvali, N., Ninnemann, U. S., Galaasen, E. V., Rosenthal, Y., Kroon, D., Oppo, D. W., Kleiven, H. F., Darling, K. F., and Kissel, C.: Rapid switches in subpolar hydrography and climate during the Last Interglacial (MIS 5e), Paleoceanography, 27, PA2207, doi:10.1029/2011PA002244, 2012.

Jackson, L. C., Kahana, R., Graham, T., Ringer, M. A., Woolings, T., Mecking, J. V., and Wood, R. A.: Global and European climate impacts of a slowdown of the AMOC in a high resolution GCM, Clim. Dynam., doi10.1007/s00382-015-2540-2, online first, 2015.

Jacobs, S. S. and Giulivi, C. F.: Large multidecadal salinity trends near the Pacific-Antarctic continental margin, J. Climate, 23, 4508–4524, 2010.

Jacobs, S. S., Jenkins, A., Giulivi, C. F., and Dutrieux, P.: Stronger ocean circulation and increased melting under Pine Island Glacier ice shelf, Nat. Geosci., 4, 519–523, 2011.

Jenkins, A. and Doake, C. S. M.: Ice-ocean interaction on Ronee Ice Shelf, Antarctica, J. Geophys. Res., 96, 791–813, 1991.
Johns, W. E., Baringer, M. O., Beal, L. M., Cunningham, S. A., Kanzow, T., Bryden, H. L., Hirschi, J. J. M., Marotzke, J., Meinen, C. S., Shaw, B., and Curry, R.: Continuous, array-based estimates of Atlantic Ocean heat transport at 26.5° N, J. Climate, 24, 2429–2449, 2011.
Johnson, G. C., Mecking, S., Sloyan, B. M., and Wijffels, S. E., Recent bottom water warming in the Pacific Ocean, J. Climate, 20, 5365–5375, 2007.
Jouzel, J., Masson-Delmotte, V., Cattani, O., Dreyfus, G., Falourd, S., Hoffmann, G., Minster, B., Nouet, J., Barnola, J. M., Chappellaz, J., Fischer, H., Gallet, J. C., Johnsen, S., Leuenberger, M., Loulergue, L., Luethi, D., Oerter, H., Parrenin, F., Raisbeck, G., Raynaud, D., Schilt, A., Schwander, J., Selmo, E., Souchez, R., Spahni, R., Stauffer, B., Steffensen, J. P., Stenni, B., Stocker, T. F., Tison, J. L., Werner, M., and Wolff, E. W.: Orbital and millennial Antarctic climate variability over the past 800,000 years, Science, 317, 793–796, 2007.
Jungclaus, J. H., Haak, H., Esch, M., Roeckner, E., and Marotzke, J.: Will Greenland melting halt the thermohaline circulation?, Geophys. Res. Lett., 33, L17708, doi:10.1029/2006GL026815, 2006.
Kandiano, E. S., Bauch, H. A., and Muller, A.: Sea surface temperature variability in the North Atlantic during the last two glacial-interglacial cycles: comparison of faunal, oxygen isotopic, and Mg/Ca-derived records, Palaeogeogr. Palaeoclim., 204, 145–164, 2004.
Keeling, R. F. and Stephens, B. B.: Antarctic sea ice and the control of Pleistocene climate instability, Paleoceanography, 16, 112–131, 2001.
Keigwin, L. D. and Jones, G. A.: Western North Atlantic evidence for millennial-scale changes in ocean circulation and climate, J. Geophys. Res., 99, 12397–12410, 1994.
Kent, D. V. and Muttoni, G.: Equatorial convergence of India and early Cenozoic climate trends, Proc. Natl. Acad. Sci. USA, 105, 16065–16070, 2008.
Khan, S. A., Kjaer, K. H., Bevis, M., Bamber, J. L., Wahr, J., Kjeldsen, K. K., Bjork, A. A., Korsgaard, N. J., Stearns, L. A., van den Broeke, M. R., Liu, L., Larsen, N. K., and Muresan, I. S.: Sustained mass loss of the northeast Greenland ice sheet triggered by regional warming, Nature Clim. Chan., 4, 292–299, doi:10.1038/nclimate2161, 2014.
Khazendar, A., Schodlok, M. P., Fenty, I., Ligtenberg, S. R. M., Rignot, E., and van den Broeke, M. R.: Observed thinning of Totten Glacier is linked to coastal polynya variability, Nature Commun., 4, 2857, doi:10.1038/ncomms3857, 2013.

Kindler, P. and Hearty, P. J.: Carbonate petrology as in indicator of climate and sea-level changes: new data from Bahamian Quaternary units, Sedimentology, 43, 381–399, 1996.
Kleinen, T., Brovkin, V., and Munhoven, G.: Carbon cycle dynamics during recent interglacials, Clim. Past Discuss., 11, 1945–1983, doi:10.5194/cpd-11-1945-2015, 2015.
Kleiven, H. F., Kissel, C., Laj, C., Ninnemann, U. S., Richter, T. O., and Cortijo, E.: Reduced North Atlantic Deep Water coeval with the glacial Lake Agassiz fresh water outburst, Science, 319, 60–64, 2008.
Kohler, P., Fischer, H., Munhoven, G., and Zeebe, R. E.: Quantitative interpretation of atmospheric carbon records over the last glacial termination, Global Biogeochem. Cy., 19, GB4020, doi:10.1029/2004GB002345, 2005.
Kopp, R. E., Simons, F. J., Mitrovica, J. X., Maloof, A. C., and Oppenheimer, M.: Probabilistic assessment of sea level during the last interglacial stage, Nature, 462, 863–867, 2009.
Kuhl, N. and Litt, T.: Quantitative time series reconstruction of Eemian temperature at three European sites using pollen data, Veget. Hist. Archaeobot., 12, 205–214, 2003.
Lacis, A. A, Schmidt, G. A., Rind, D., and Ruedy, R. A.: Atmospheric CO_2: Principal control knob governing Earth's temperature, Science, 330, 356–359, doi:10.1126/science.1190653, 2010.
Lacis, A. A., Hansen, J. E., Russell, G. L., Oinas, V., and Jonas, J.: The role of long-lived greenhouse gases as principal LW control knob that governs the global surface temperature for past and future climate change, Tellus B, 65, 19734, doi:10.3402/tellusb.v65i0.19734, 2013.
Lambeck, K. and Chappell, J.: Sea level change through the last glacial cycle, Science, 292, 679–686, 2001.
Lambeck, K., Rouby, H., Purcell, A., Sun, Y., and Sambradge, M.: Sea level and global ice volumes from the Last Glacial Maximum to the Holocene, Proc. Natl. Acad. Sci. USA, 111, 15296–15303, 2014.
Land, L. S., Mackenzie, F. T., and Gould, S. J.: The Pleistocene history of Bermuda, Bull. Geol. Soc. Amer., 78, 993–1006, 1967.
Landais, A., Masson-Delmotte, V., Stenni, B., Selmo, E., Roche, D. M., Jouzel, J., Lambert, F., Guillevic, M., Bazin, L., Arzel, O., Vinther, B., Gkinis, V., and Popp, T.: A review of the bipolar see-saw from synchronized and high resolution ice core water stable isotope records from Greenland and East Antarctica, Quaternary Sci. Rev., 114, 18–32, 2015.

Large, W. G., McWilliams, J. C., and Doney, S. C.: Oceanic vertical mixing: a review and a model with a nonlocal boundary layer parameterization, Rev. Geophys., 32, 363–403, 1994.
Lea, D. W., Martin, P. A., Pak, D. K., and Spero, H. J.: Reconstructing a 350 ky history of sea level using planktonic Mg/Ca and oxygen isotope records from a Cocos Ridge core, Quaternary Sci. Rev., 21, 283–293, 2002.
LeGrande, A. N. and Schmidt, G. A.: Ensemble, water isotope-enabled, coupled general circulation modeling insights into the 8.2 ka event, Paleoceanography, 23, PA3207, doi:10.1029/2008PA001610, 2008.
LeGrande, A. N., Schmidt, G. A., Shindell, D. T., Field, C. V., Miller, R. L., Koch, D. M., Faluvegi, G., and Hoffmann, G.: Consistent simulations of multiple proxy responses to an abrupt climate change event, Proc. Natl. Acad. Sci. USA, 103, 837–842, 2006.
Lehman, S. J., Sachs, J. P., Crotwell, A. M., Keigwin, L. D., and Boyle, E. A.: Relation of subtropical Atlantic temperature, high-latitude ice rafting, deep water formation, and European climate 130,000-60,000 years ago, Quatern. Sci. Rev., 21, 1917–1924, 2002.
Levitus, S. and Boyer, T. P.: World ocean atlas 1994, vol. 4: Temperature, NOAA Atlas NESDIS 4, pp. 177, U.S. Government Printing Office, Washington, DC, 1994.
Levitus, S., Antonov, J., and Boyer, T. P.: World ocean atlas 1994, vol. 3: Salinity, NOAA Atlas NESDIS 3, pp. 99, US Government Printing Office, Washington, DC, 1994.
Li, C., Battisti, D. S., Schrag, D. P., and Tziperman, E.: Abrupt climate shifts in Greenland due to displacements of the sea ice edge, Geophys. Res. Lett., 32, L19702, doi:10.1029/2005GL023492, 2005.
Li, C., Battisti, D. S., and Bitz, C. M.: Can North Atlantic sea ice anomalies account for Dansgaard-Oeschger climate signals?, J. Climate, 23, 5457–5475, 2010.
Lisiecki, L. E. and Raymo, M. E.: A Pliocene-Pleistocene stack of 57 globally distributed benthic δ^{18}O records, Paleoceanography, 20, PA1003, doi:10.1029/2004PA001071, 2005.
Lozier, M. S.: Overturning in the North Atlantic, Ann. Rev. Mar. Sci., 4, 291–315, 2012.
Lumpkin, R. and Speer, K.: Global ocean meridional overturning, J. Phys. Oceanogr., 37, 2550–2562, 2007.
Luthi, D., Le Floch, M., Bereiter, B., Blunier, T., Barnola, J.M., Siegenthaler, U., Raynaud, D., Jouzel, J., Fischer, H., Kawamura, K., and Stocker, T. F.: High-resolution carbon dioxide concentration record 650,000-800,000 years before present, Nature, 453, 379–382, 2008.
MacAyeal, D. R.: Binge/purge oscillations of the Laurentide ice-sheet as a cause of the North-Atlantic's Heinrich events, Paleoceanography, 8, 775–784, 1993.

Manabe, S. and Stouffer, R. J.: Multiple-century response of a coupled ocean-atmosphere model to an increase of atmospheric carbon dioxide, J. Climate, 7, 5–23, 1994.
Manabe, S. and Stouffer, R. J.: Simulation of abrupt climate change induced by freshwater input to the North Atlantic Ocean, Nature, 378, 165–167, 1995.
Marcott, S. A., Clark, P. U., Padman, L., Klinkhammer, G. P., Springer, S. R., Liu, Z., Otto-Bliesner, B. L., Carlson, A. E., Ungerer, A., Padman, J., He,. F., Cheng, J. and Schmittner, A.: Ice-shelf collapse from subsurface warming as a trigger for Heinrich events, Proc. Natl. Acad. Sci. USA, 108, 13415–13419, doi:10.1073/pnas.1104772108, 2011.
Marcott, S. A., Bauska, T. K., Buizert, C., Steig, E. J., Rosen, J. L., Cuffey, K. M., Fudge, T. J., Severinghaus, J. P., Ahn, J., Kalk, M. L., McConnell, J. R., Sowers, T., Taylor, K. C., White, J. W. C., and Brook, E. J.: Centennial-scale changes in the global carbon cycle during the last deglaciation, Nature, 514, 616–619, 2014.
Marshall, G. J.: Trends in the Southern Annular Mode from observations and reanalyses, J. Climate, 16, 4134–4143, 2003.
Marshall, J. and Speer, K.: Closure of the meridional circulation through Southern Ocean upwelling, Nat. Geosci., 5, 171–180, 2012.
Martin, J. H. and Fitzwater, S. E.: Iron deficiency limits phytoplnnkton growth in the north-east Pacific subarctic, Nature, 331, 341–343, 1988.
Martinez-Garcia, A., Sigman, D. M., Ren, H., Anderson, R., Straub, M., Hodell, D., Jaccard, S., Eglinton, T. I., and Haug, G. H.: Iron fertilization of the subantarctic ocean during the last ice age, Science, 343, 1347–1350, 2014.
Martinson, D. G., Pisias, N. G., Hays, J. D., Imbrie, J., Moore, T. C., and Shackleton, N. J.: Age dating and the orbital theory of the ice ages: development of a high-resolution 0 to 300,000-year chronostratigraphy, Quaternary Res., 27, 1–29, 1987.
Masson-Delmotte, V., Jouzel, J., Landais, A., Stievenard, M., Johnsen, S. J., White, J. W. C., Werner, M., Sveinbjornsdottir, A., and Fuhrer, K.: GRIP deuterium excess reveals rapid and orbital-scale changes in Greenland moisture origin, Science, 309, 118–121, doi:10.1126/science.1108575, 2005.
Masson-Delmotte, V., Dreyfus, G., Braconnot, P., Johnsen, S., Jouzel, J., Kageyama, M., Landais, A., Loutre, M.-F., Nouet, J., Parrenin, F., Raynaud, D., Stenni, B., and Tuenter, E.: Past temperature reconstructions from deep ice cores: relevance for future climate change, Clim. Past, 2, 145–165, doi:10.5194/cp-2-145-2006, 2006.

Masson-Delmotte, V., Stenni, B., Pol, K., Braconnot, P., Cattani, O., Falourd, S., Kageyama, M., Jouzel, J., Landais, A., Minster, B., Barnola, J. M., Chappellaz, M., Krinner, G., Johnsen, S., Röthlisberger, R., Hansen, J., Mikolajewicz, U., and Otto-Bliesner, B.: EPICA Dome C record of glacial and interglacial intensities, Quaternary Sci. Rev., 29, 113–128, doi:10.1016/j.quascirev.2009.09.030, 2010.

Masson-Delmotte, V., Buiron, D., Ekaykin, A., Frezzotti, M., Gallée, H., Jouzel, J., Krinner, G., Landais, A., Motoyama, H., Oerter, H., Pol, K., Pollard, D., Ritz, C., Schlosser, E., Sime, L. C., Sodemann, H., Stenni, B., Uemura, R., and Vimeux, F.: A comparison of the present and last interglacial periods in six Antarctic ice cores, Clim. Past, 7, 397–423, doi:10.5194/cp-7-397-2011, 2011.

Masson-Delmotte, V., Schulz, M., Abe-Ouchi, A., Beer, J., Ganopolski, A., Gonzalez Rouco, J.F., Jansen, E., Lambeck, K., Luterbacher, J., Naish, T., Osborn, T., Otto-Bliesner, B., Quinn, T., Ramexh, R. Rojas, M., Shao, X., and Timmermann, A.: Information from paleoclimate Archives, in: Climate Change 2013: The Physical Basis, Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge Univesity Press, Cambridge, United Kingdom, 2013.

McCulloch, M. T. and Esat, T.: The coral record of last interglacial sea levels and sea surface temperatures, Chem. Geol., 169, 107–129, 2000.

Menviel, L., Joos, F., and Ritz, S. P.: Simulating atmospheric CO_2, ^{13}C and the marine carbon cycle during the last glacial-interglacial cycle: possible role for a deepening of the mean remineralization depth and an increase in the oceanic nutrient inventory, Quaternary Sci. Rev., 56, 46–68, 2012.

Mercer, J. H.: West Antarctic ice sheet and CO_2 greenhouse effect: a threat of disaster, Nature, 271, 321–325, 1978.

Miller, R. L., Schmidt, G. A., Nazarenko, L. S., Tausnev, N., Bauer, S. E., Del Genio, A. D., Kelley, M., Lo, K. K., Ruedy, R., Shindell, D. T., Aleinov, I., Bauer, M., Bleck, R., Canuto, V., Chen, Y.-H., Cheng, Y., Clune, T. L., Faluvegi, G., Hansen, J. E., Healy, R. J., Kiang, N. Y., Koch, D., Lacis, A., LeGrande, A. N., Lerner, J., Menon, S., Oinas, V., Pérez García-Pando, C., Perlwitz, J. P., Puma, M., Rind, D., Romanou, A., Russell, G., Sato, M., Sun, S., Tsigaridis, K., Unger, N., Voulgarakis, A., Yao, M.-S., and Zhang, J.: CMIP5 historical simulations (1850–2012) with GISS ModelE2, J. Adv. Model. Earth Syst., 6, 441–477, doi:10.1002/2013MS000266, 2014.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

Morlighem, M., Rignot, E., Mouginot, J., Seroussi, H., and Larour, E.: Deeply incised submarine glacial valleys beneath the Grenland ice sheet, Nat. Geosci., 7, 418–422, 2014.

Munk, W. and Wunsch, C.: Abyssal recipes II: energetics of tidal and wind mixing, Deep-Sea Res. Pt. I, 45, 1977–2010, 1998.

Neff, W., Compo, G., Ralph, F. M., and Shupe, M. D.: Continental heat anomalies and the extreme melting of the Greenland ice surface in 2012 and 1989, J. Geophys. Res. Atmos., 119, 6520–6536, 2014.

Nerem, R. S., Chanmber, D. P., Choe, C., and Mitchum, G. T.: Estimating mean sea level change from the TOPEX and Jason altimeter missions, Marine Geodesy, 33, 435–446, 2010.

Neumann, A. C. and Hearty, P. J.: Rapid sea-level changes at the close of the last interglacial (substage 5e) recorded in Bahamian island geology, Geology 24, 775–778, 1996.

Neumann, A. C. and MacIntyre, I.: Reef response to sea level rise: keep-up, catch-up or give-up, Proc. 5th International Coral Reef Congress, Tahiti, 3, 105–110, 1985.

Neumann, A. C. and Moore, W. S.: Sea-level events and Pleistocene coral ages in the northern Bahamas, Quaternary Res., 5, 215–224, 1975.

NGRIP (North Greenland Ice Core Project members): High-resolution record of Northern Hemisphere climate extending into the last interglacial period: Nature, 4341, 147–151, 2004.

Ohkouchi, N., Eglinton, T. I., Keigwin, L. D., and Hayes, J. M.: Spatial and temporal offsets between proxy records in a sediment drift, Science, 298, 1224–1227, 2002.

Ohmura, A.: Completing the world glacier inventory, Ann. Glaciol., 50, 144–148, 2009.

Ohshima, K. I., Fukamachi, Y., Williams, G. D., Nihashi, S., Roquet, F., Kitade, Y., Tamura, T., Hirano, D., Herraiz-Borreguero, L., Field, I., Hindell, M., Aoki, S., and Watasuchi, M.: Antarctic bottom water production by intense sea-ice formation in the Cape Darnley polynya, Nat. Geosci., 6, 235–240, 2013.

O'Leary, M. J., Hearty, P. J., Thompson, W. G., Raymo, M. E., Mitrovica, J. X., and Webster, J. M.: Ice sheet collapse following a prolonged period of stable sea level during the last interglacial, Nat. Geosci., 6, 796–800, doi:10.1038/NGEO1890, 2013.

Oppo, D. W., McManus, J. F., and Cullen, J. L.: Evolution and demise of the last interglacial warmth in the subpolar North Atlantic, Quaternary Sci. Rev., 25, 3268–3277, 2006.

Orsi, A. H., Johnson, G. C., and Bullister, J. L.: Circulation, mixing, and production of Antarctic bottom water, Progr. Oceanogr., 43, 55–109, 1999.

Paillard, D.: Glacial cycles: toward a new paradigm, Rev. Geophys., 39, 325–346, 2001.

Palaeosens Project members, Rohling, E. J., Sluijs, A., Dijkstra, H. A., Kohler, P., van de Wal, S. W., von der Heydt, A. S., Beerling, D.J., Berger, A., Bijl, A., Crucifix, M., DeConto, R., Drijfhout, S. S., Fedorov, A., Foster, G. L., Ganopolski, A., Hansen, J., Honisch, B., Hooghiemstra, H., Huber, M., Huybers, P., Knutti, R., Lea, D. W., Lourens, L. J., Lunt, D., Masson-Delmotte, V., Medina-Elisalde, M., Otto-Bliesner, B., Pagani, M., Palike, H., Renssen, H., Royer, D. L., Siddall, M., Valdes, P., Zachos, J. C., and Zeebe, R. E.: Making sense of palaeoclimate sensitivity, Nature, 491, 683–691, doi:10.1038/nature11574, 2012.

Paolo, F. S., Fricker, H. A., and Padman, L.: Volume loss from Antarctic ice shelves is accelerating, Science, 348, 327–331, 2015.

Parrenin, F., Masson-Delmotte, V., Kohler, P., Raynaud, D., Paillard, D., Schwander, Barbante, C., Landais, A., Wegner, A., and Jouzel, J.: Synchronous change of atmospheric CO_2 and Antarctic temperature during the last deglacial warming, Science, 339, 1060–1063, 2013.

Pedro, J. B., Rasmussen, S. O., and van Ommen, T. D.: Tightened constraints on the time-lag between Antarctic temperature and CO_2 during the last deglaciation, Clim. Past, 8, 1213–1221, doi:10.5194/cp-8-1213-2012, 2012.

Peltier, W. R. and Fairbanks, R. G.: Global glacial ice volume and Last Glacial Maximum duration from an extended Barbados sea level record, Quarternary Sci. Rev., 25, 3322–3337, 2006.

Petersen, S. V., Schrag, D. P., and Clark, P. U.: A new mechanism for Dansgaard-Oeschger cycles, Paleoceanography, 28, 24–30, 2013.

Pol, K., Masson-Delmotte, V., Cattani, O., Debret, M., Falourd, S., Jouzel, J., Landais, A., Minster, B., Mudelsee, M., Schulz, M., and Stenni, B.: Climate variability features of the last interglacial in the East Antarctic EPICA Dome C ice core, Geophys. Res. Lett., 41, 4004–4012, doi:10.1002/2014GL059561, 2014.

Pollard, D., DeConto, R. M., and Alley, R. B.: Potential Antarctic ice sheet retreat driven by hydrofracturing and ice cliff failure, Earth Planet. Sci. Lett., 412, 112–121, 2015.

Pritchard, H. D., Ligtenberg, S. R. M., Fricker, H. A., Vaughan, D. G., van den Broeke, M. R., and Padman, L.: Antarctic ice-sheet loss driven by basal melting of ice shelves, Nature, 484, 502–505, 2012.

Purkey, S. G. and Johnson, G. S.: Antarctic bottom water warming and freshening: contributions to sea level rise, ocean freshwater budgets, and global heat gain, J. Climate, 26, 6105–6122, 2013.

Rahmstorf, S.: Rapid climate transitions in a coupled ocean-atmosphere model, Nature, 372, 82–85, 1994.

Rahmstorf, S.: Bifurcations of the Atlantic thermohaline circulation in response to changes in the hydrological cycle, Nature, 378, 145–149, 1995.

Rahmstorf, S.: On the freshwater forcing and transport of the Atlantic thermohaline circulation. Clim. Dynam., 12, 799–811, 1996.

Rasmussen, S. O., Bigler, M., Blockley, S. P., Blunier, T., Buchardt, S. L., Clausen, H. B., Cvijanovic, I., Dahl-Jensen, D., Johnsen, S. J., Fischer, H., Gkinis, V., Guillevic, M., Hoek, W. Z., Lowe, J. J., Pedro, J. B., Popp, T., Seierstad, I. K., Steffensen, J. P., Svensson, A. M., Vallelonga, P., Vinther, B. M., Walker, M. J. C., Wheatley, J. J., and Winstrup, M.: A stratigraphic framework for abrupt climatic changes during the Last Glacial period based on three synchronized Greenland ice-core records: refining and extending the INTIMATE event stratigraphy, Quaternary Sci. Rev., 106, 14–28, 2014.

Rasmussen, T. L., Oppo, D. W., Thomsen, E., and Lehman, S. J.: Deep sea records from the southeast Labrador Sea: ocean circulation changes and ice-rafting events during the last 160,000 years, Paleoceanography, 18, 1018, doi:10.1029/2001PA000736, 2003.

Raven, J. A. and Falkowski, P. G.: Oceanic sinks for atmospheric CO_2, Plant Cell Environ., 22, 741–755, 1999.

Raymo, M. E.: The timing of major climate terminations, Paleocean. 12, 577–585, 1997.

Rayner, D., Hirschi, J. J.-M., Kanzow, T., Johns, W. E., Wright, P. G., Frajka-Williams, E., Bryden, H. L., Meinen, C. S., Baringer, M. O., Marotzke, J., Beal, L. M., and Cunningham, S. A.: Monitoring the Atlantic meridional overturning circulation, Deep Sea Res. Pt. II, 58, 1744–1753, 2011.

Rignot, E. and Jacobs, S. S.: Rapid bottom melting widespread near Antarctic ice sheet grounding lines, Science, 296, 2020–2023, 2002.

Rignot, E. and Steffen, K.: Channelized bottom melting and stability of floating ice shelves, Geophys. Res. Lett., 35, L02503, doi:10.1029/2007GL031765, 2008.

Rignot, E., Velicogna, I., van den Broeke, M. R., Monaghan, A., and Lenaerts, J. T. M.: Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise, Geophys. Res. Lett., 38, L05503, doi:10.1029/2011GL046583, 2011.

Rignot, E., Jacobs, S., Mouginot, J., and Scheuchl, B.: Ice shelf melting around Antarctica, Science, 341, 266–270, 10.1126/science.1235798, 2013.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

Rignot, E., Mouginot, J., Morlighem, M., Seroussi, H., and Scheuchl, B.: Widespread, rapid grounding line retreat of Pine Island, Thwaites, Smith, and Kohler glaciers, West Antarctica, from 1992 to 2011, Geophys. Res. Lett., 41, 3502–3509, 2014.

Rinterknecht, V., Jomelli, V., Brunstein, D., Favier, V., Masson-Delmotte, V., Bourles, D., Leanni, L., and Schlappy, R.: Unstable ice stream in Greenland during the Younger Dryas cold event, Geology, 42, 759–762, 2014.

Rintoul, S.: Rapid freshening of Antarctic Bottom Water formed in the Indian and Pacific oceans, Geophys. Res. Lett., 34, L06606, doi:10.1029/2006GL028550, 2007.

Robinson, A., Calov, R., and Ganopolski, A.: Multistability and critical thresholds of the Greenland ice sheet, Nature Clim. Change, 2, 429–432, doi:10.1038/NCLIMATE1449, 2012.

Roche, D., Paillard, D., and Cortijo, E.: Constraints on the duration and freshwater release of Heinrich event 4 through isotope modelling, Nature, 432, 379–382, 2004.

Roemmich, D., Church, J., Gilson, J., Monselesan, Sutton, P., and Wijffels, S.: Unabated planetary warming and its ocean structure since 2006, Nature Clim. Chan., 5, 240–245, 2015.

Rohling, E. J., Grant, K., Hemleben, Ch., Siddall, M., Hoogakker, B. A. A., Bolshaw, M., and Kucera, M.: High rates of sea-level rise during the last interglacial period, Nat. Geosci., 1, 38–42, 2008.

Rohling, E. J., Grant, K., Bolshaw, M., Roberts, A., Siddall, M., Hemleben, C., and Kucera, M.: Antarctic temperature and global sea level closely coupled over the past five glacial cycles, Nat. Geosci., 2, 500–504, 2009.

Ruddiman, W. F.: The atmospheric greenhouse era began thousands of years ago, Clim. Change, 61, 261–293, 2003.

Ruddiman, W. F.: The Anthropocene, Ann. Rev. Earth Plan. Sci., 41, 45–68, doi:10.1146/annurev-earth-050212-123944, 2013.

Russell, G. L., Miller, J. R., and Rind, D.: A coupled atmosphere-ocean model for transient climate change studies, Atmos. Ocean, 33, 683–730, 1995.

Ruth, U., Barnola, J.-M., Beer, J., Bigler, M., Blunier, T., Castellano, E., Fischer, H., Fundel, F., Huybrechts, P., Kaufmann, P., Kipfstuhl, S., Lambrecht, A., Morganti, A., Oerter, H., Parrenin, F., Rybak, O., Severi, M., Udisti, R., Wilhelms, F., and Wolff, E.: "EDML1": a chronology for the EPICA deep ice core from Dronning Maud Land, Antarctica, over the last 150 000 years, Clim. Past, 3, 475–484, doi:10.5194/cp-3-475-2007, 2007.

Rye, C. D., Naveira Garabato, A. C., Holland, P. R., Meredith, M. P., Norser, A. J. G., Hughes, C.W., Coward, A. C., and Webb, D. J.: Rapid sea-level rise along the Antarctic margins in

response to increased glacial discharge, Nat. Geosci., doi:10.1038/NGEO2230, onine first, 2014.

Sachs, J. P. and Lehman, S. J.: Subtropical North Atlantic temperatures 60,000-30,000 years ago, Science, 286, 756–759, 1999.

Sato, M., Hansen, J. E., McCormick, M. P., and Pollack, J. B.: Stratospheric aerosol optical depths, 1850–1990, J. Geophys. Res., 98, 22987–22994, doi:10.1029/93JD02553, 1993.

Schilt, A., Baumgartner, M., Schwander, J., Buiron, D., Capron, E., Chappellaz, J., Loulergue, L., Schupach, S., Spahni, R., Fischer, H., and Stocker, T. F.: Atmospheric nitrous oxide during the last 140,000 years, Earth Planet. Sci. Lett., 300, 33–43, 2010.

Schimidtko, S., Heywood, K. J., Thompson, A. F., and Aoki, S.: Multidecadal warming of Antarctic waters, Science, 346, 1227–1231, 2014.

Schmidt, G. A., Ruedy, R., Hansen, J., Aleinov, I., Bell, N., Bauer, M., Bauer, S., Cairns, B., Canuto, V., Cheng, Y., Del Genio, A., Faluvegi, G., Friend, A. D., Hall, T. M., Kelley, M., Kiang, N. Y., Koch, D., Lacis, A. A., Lerner, J., Lo, K. K., Miller, R. L., Nazarenko, L., Oinas, V., Perlwitz, J. P., Perlwitz, J., Rind, D., Romanou, A., Russell, G. L., Sato, M., Shindell, D. T., Stone, P. H., Sun, S., Tausnev, N., Thresher, D., Yao, M. S.: Present day atmospheric simulations using GISS modelE: comparison to in-situ, satellite and reanalysis data, J. Climate, 19, 153–192, 2006.

Schmitt, J., Schneider, R., Elsig, J., Leuenberger, D., Lourantou, A., Chappellaz, J., Kohler, P., Joos, F., Stocker, T. F., Leuenberger, M., and Fischer, H.: Carbon isotope constraints on the deglacial CO_2 rise from ice cores, Science, 336, 711–714, 2012.

Schmittner, A., Latif, M., and Schneider, B.: Model projections of the North Atlantic thermohaline circulation for the 21st century assessed by observations, Geophys. Res. Lett., 32, L23710, doi:10.1029/2005GL024368, 2005.

Scholz, D. and Mangini, A.: How precise are U-series coral ages?, Cosmochim. Acta, 71, 1935–1948, 2007.

Schulz, M.: On the 1470-year pacing of Dansgaard-Oeschger warm events, Paleoceanography, 17, 1014, doi:10.1029/2000PA000571, 2002.

Shaffer, G., Olsen, S. M., and Bjerrum, C. J.: Ocean subsurface warming as a mechanism for coupling Dansgaard-Oeschger climate cycles and ice-rafting events, Geophys. Res. Lett., 31, L24202, doi:10.1029/2004GL020968, 2004.

Shakun, J. D., Clark, P. U., He, F., Marcott, S. A., Mix, A. C., Liu, Z., OttoBliesner, B., Schmittner, A., and Bard, E.: Global warming preceded by increasing carbon dioxide concentrations during the last deglaciation, Nature, 484, 49–54, 2012.

Sheen, K. L., Naveira Garabato, A. C., Brearley, J. A., Meredith, M. P., Polzin, K. L., Smeed, D. A., Forryan, A., King, B. A., Sallee, J. B., St. Laurent, L., Thurnherr, A. M., Toole, J. M., Waterman, S. N., and Watson, A. J.: Eddy-induced variability in Southern Ocean abyssal mixing on climatic timescales, Nat. Geosci., 7, 577–582, 2014.

Shepherd, A., Ivins, E. R., Geruo, A., Barletta, V. R., Bentley, M. J., Bettadpur, S., Briggs, K. H., Bromwich, D. H., Forsberg, R., Galin, N., Horwath, M., Jacobs, S., Joughin, I., King, M. A., Lenaerta, J. T. M, Li, J., Lightenberg, S. R. M., Luckman, A., Luthcke, S. B., McMillan, M., Meister, R., Milne, G., Mouginot, J., Muir, A., Bicolas, J. P., Paden, J., Payne, A. J., Pritchard, H., Rignot, E., Rott, H., Sorensen, L. S., Scambos, T. A., Scheuchl, B., Schrama, E. J. O., Smith, B., Sundal, A. V., van Angelen, J. H., van de Berg, W. J., van den Broeke, M. R., Vaughan D. G., Velicogna, I., Wahr, J., Whitehouse, P. L., Wingham, D. J., Yi, D., Young, D., and Zwally, H. J.: A reconciled estimate of ice-sheet mass balance, Science, 338, 1183–1189, 2012.

Sigman, D. M. and Boyle, E. A.: Glacial/interglacial variations in atmospheric carbon dioxide, Nature, 407, 859–869, 2000.

Sigmond, M. and Fyfe, J. C.: The Antarctic ice response to the ozone hole in climate models, J. Climate, 27, 1336–1342, 2014.

Sirocko, F., Seelos, K., Schaber, K., Rein, B., Dreher, F., Diehl, M., Lehne, R., Jager, K., Krbetshek, M., and Degering, D.: A late Eemian aridity pulse in central Europe during the last glacial inception, Nature, 436, 833–836, 2005.

Skinner, L. C., Fallon, S., Waelbroeck, Michel, E., and Barker, S.: Ventilation of the deep Southern Ocean and deglacial CO_2 rise, Science, 328, 1147–1151, 2010.

Solomon, S., Daniel, J. S., Sanford, T. J., Murphy, D. M., Plattner, G. K., Knutti, R., and Friedlingstein, P.: Persistence of climate changes due to a range of greenhouse gases, Proc. Natl. Acad. Sci. USA, 107, 18354–18359, 2010.

Srokosz, M., Baringer, M., Bryden, H., Cunningham, S., Delowrth, T., Lozier, S., Marotzke, J., and Sutton, R.: Past, present, and future changes in the Atlantic meridional overturning circulation, Bull. Amer. Meteorol. Soc., 93, 1663–1676, 2012.

Stenni, B., Buiron, D., Frezzotti, M., Albani, S., Barbante, C., Bard, E., Barnola, J. M., Baroni, M., Baumgartner, M., Bonazza, M., Capron, E., Castellano, E., Chappellaz, J., Dekmonte,

B., Falourd, S., Genoni, L., Iacumin, P., Jouzel, J., Kipfstuhl, S., Landais, A., Lemieux-Dudon, B., Maggi, V., Masson-Delmotte, V., Mazzola, C., Minster, B., Montagnat, M., Mulvaney, R., Narcisi, B., Oerter, H., Parrenin, F., Petit, J. R., Ritz, C., Scarchilli, C., Schilt, A., Schupbach, S., Schwander, J., Selmo, E., Severi, M., Stocker, T. F., and Udisti, R.: Expression of the bipolar see-saw in Antarctic climate records during the last deglaciation, Nat. Geosci., 4, 46–49, 2011.

Stirling, C. H., Esat, T. M., Lambeck, K., and McCulloch, M. T.: Timing and duration of the last interglacial: evidence for a restricted interval of widespread coral reef growth, Earth Planet. Sci. Lett., 160, 745–762, 1998.

Stocker, T. F.: The seesaw effect, Science, 282, 61–62, 1998.

Stocker, T. F. and Johnsen, S. J.: A minimum thermodynamic model for the bipolar seesaw, Paleoceanography, 18, 1087, doi:10.1029/2003PA000920, 2003.

Stocker, T. F. and Wright, D. G.: Rapid transitions of the ocean's deep circulation induced by changes in surface water fluxes, Nature, 351, 729–732, 1991.

Sutterley, T., Velicogna, I., Rignot, E., Mouginot, J., Flament, T., van den Broeke, M., van Wessem, J. M., and Reijmer, C. H.: Mass loss of the Amundsen Sea Embayment of West Antarctica from four independent techniques, Geophys. Res. Lett., 4, 8421–8428, 2014.

Swingedouw, D., Braconnot, P., Delecluse, P., Guilyardi, E., and Marti, O.: Quantifying the AMOC feedbacks during a 2× CO_2 stabilization experiment with land-ice melting, Clim. Dynam., 29, 521–534, 2007.

Swingedouw, D., Mignot, J., Braconnot, P., Mosquet, E., Kageyama, M., and Alkama, R.: Impact of freshwater release in the North Atlantic under different climate conditions in an OAGCM, J. Climate, 22, 6377–6403, 2009.

Swingedouw, D., Rodehacke, C. B., Olsen, S. M., Menary, M., Gao, Y., Mikolajewicz, and Mignot, J.: On the reduced sensitivity of the Atlantic overturning to Greenland ice sheet melting in projections: a multi-model assessment, Clim. Dynam., 44, 3261–3279, doi:10.1007/s00382-014-2270-x, online first, 2014.

Taft, W. H., Arrington, F., Haimoritz, A., MacDonald, C., and Woolheater, C.: Lithification of modern carbonate sediments at Yellow Bank, Bahamas, Bull. Marine Sci. Gulf Caribbean, 18, 762–828, 1968.

Talley, L. D.: Closure of the global overturning circulation through the Indian, Pacific, and Southern Oceans, Oceanography, 26, 80–97, 2013.

Tedesco, M., Fettweis, X., Mote, T., Wahr, J., Alexander, P., Box, J. E., and Wouters, B.: Evidence and analysis of 2012 Greenland records from spaceborne observations, a regional climate model and reanalysis data, The Cryosphere, 7, 615–630, doi:10.5194/tc-7-615-2013, 2013.
Thompson, D. W. J., Solomon, S., Kushner, P. J., England, M. H., Grise, K. M., and Karoly, D. J.: Signatures of the Antarctic ozone hole in Southern Hemisphere surface climate change, Nat. Geosci., 4, 741–749, 2011.
Thompson, W. G. and Goldstein, S. L.: Open-system coral ages reveal persistent suborbital sea-level cycles, Science, 308, 401–404, 2005.
Thompson, W. G., Curran, H. A., Wilson, M. A., and White, B.: Sea-level oscillations during the last interglacial highstand recorded by Bahamas corals, Nat. Geosci., 4, 684–687, 2011.
Thornalley, D. J. R., Barker, S., Becker, J., Hall, I. R., and Knorr, G.: Abrupt changes in deep Atlantic circulation during the transition to full glacial conditions, Paleoceanography, 28, 253–262, 2013.
Toggweiler, J. R.: Variation of atmospheric CO_2 by ventilation of the ocean's deepest water, Paleoceanography, 14, 571–588, 1999.
Toggweiler, J. R., Russell, J. L., and Carson, S. R.: Midlatitude westerlies, atmospheric CO_2, and climate change during the ice ages, Paleoceanography, 21, PA2005, doi:10.1029/2005PA001154, 2006.
Tormey, B. R.: Run over, run up, and run out: a storm wave origin for fenestral porosity in last interglacial eolianites of the Bahamas, Geological Society of America, 64th Annual Meeting, Session 12, 19–20 March 2015.
Tschumi, T., Joos, F., Gehlen, M., and Heinze, C.: Deep ocean ventilation, carbon isotopes, marine sedimentation and the deglacial CO_2 rise, Clim. Past, 7, 771–800, doi:10.5194/cp-7-771-2011, 2011.
United States National Climate Assessment (USNCA): available at: http://nca2014.globalchange.gov/ (last access: 1 December 2014), 2014.
Vacher, H. L. and Rowe, M. P.: Geology and hydrogeology of Bermuda, in: Geology and Hydrogeology of Carbonate Islands, edited by: Vacher, H. L. and Quinn, T., Devel. Sedimentol., 54, 35–90, 1997.
Vaughan, D. G., Bamber, J. L., Giovinetto, M., Russell, J., and Cooper, A. P. R.: Reassessment of net surface mass balance in Antarctica, J. Climate, 12, 933–946, 1999.

Velicogna, I., Sutterley, T. C., and van den Broeke, M. R.: Regional acceleration in ice mass loss from Greenland and Antarctica using GRACE time-variable gravity data, Geophys. Res. Lett., 41, 8130–8137, doi:10.1002/2014GL061052, 2014.
Veres, D., Bazin, L., Landais, A., Toyé Mahamadou Kele, H., Lemieux-Dudon, B., Parrenin, F., Martinerie, P., Blayo, E., Blunier, T., Capron, E., Chappellaz, J., Rasmussen, S. O., Severi, M., Svensson, A., Vinther, B., and Wolff, E. W.: The Antarctic ice core chronology (AICC2012): an optimized multi-parameter and multi-site dating approach for the last 120 thousand years, Clim. Past, 9, 1733–1748, doi:10.5194/cp-9-1733-2013, 2013.
Visbeck, M., Marshall, J., Haine, T., and Spall, M.: Specification of eddy transfer coefficients in coarse resolution ocean circulation models, J. Phys. Oceanogr., 27, 381–402, 1997.
Vizcaino, M., Mikolajewicz, U., Groger, M., Maier-Reimer, E., Schurgers, G. and Winguth, A. M. E.: Long-term ice sheet-climate interactions under anthropogenic greenhouse forcing simulated with a complex Earth System Model, Clim. Dynam., 31, 665–690, 2008.
Wanless, H. R. and Dravis, J. J.: Carbonate Environments and Sequences of Calcos Platform. Field Trip Guidebook T374, 28th International Geological Congress, American Geophysical Union, 75 pp., 1989.
Watson, A. J. and Garabato, A. C. N.: The role of Southern Ocean mixing and upwelling in glacial-interglacial atmospheric CO_2 change, Tellus, 58B, 73–87, 2006.
Weaver, A. J., Eby, M., Kienast, M., and Saenko, O. A.: Response of the Atlantic meridional overturning circulation to increasing atmospheric CO_2: sensitivity to mean climate state, Geophys. Res. Lett., 34, L05708, doi:10.1029/2006GL028756, 2007.
Weber, M. E., Clark, P. U., Kuhn, G., Timmermann, A., Sprenk, D., Gladstone, R., Zhang, X., Lohmann, G., Menviel, L., Chikamoto, M. O., Friedrich, T., and Ohlwein, C.: Millennial-scale variability in Antarctic ice-sheet discharge during the last deglaciation, Nature, 510, 134–138, 2014.
White, B., Curran, H. A., and Wilson, M. A.: Bahamian coral reefs yield evidence of a brief sea-level lowstand during the last interglacial, Carbonates Evaporites, 13, 10–22, 1998.
Williams, G. D., Meijers, A. J. S., Poole, A., Mathiot, P., Tamura, T., and Klocker, A.: Late winter oceanography off the Sabrina and BANZARE coast (117–128° E), East Antarctica, Deep-Sea Res. Pt. II, 58, 1194–1210, 2011.
Wilson, M. A., Curran, H. A., and White, B.: Paleontological evidence of a brief sea-level event during the last interglacial, Lethaia, 31, 241–250, 1998.
Wunsch, C.: What is the thermohaline circulation?, Science, 298, 1179–1180, 2002.

Wunsch, C.: Quantitative estimate of the Milankovitch-forced contribution to observed Quaternary climate change, Quaternary Sci. Rev., 23, 1001–1012, 2004.

Wunsch, C. and Ferrari, R.: Vertical mixing, energy, and the general circulation of the oceans, Ann. Rev. Fluid Mech, 36, 281–314, 2004.

Yokoyama, Y., Esat, T. M., and Lambeck, K.: Coupled climate and sea-level changes deduced from Huon Peninsula coral terraces of the last ice age, Earth Planet. Sci. Lett., 193, 579–587, 2001.

Zachos, J., Pagani, M., Sloan, L., Thomas, E., and Billups, K.: Trends, rhythms, and aberrations in global climate 65 Ma to present, Science, 292, 686–693, 2001.

Figure 1. Two boulders (#1 and #2 of Hearty, 1997) on coastal ridge of North Eleuthera Island, Bahamas. Scale: person in both photos = 1.6 m. Estimated weight of largest boulder (#1, on left) is ~2300 tons.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

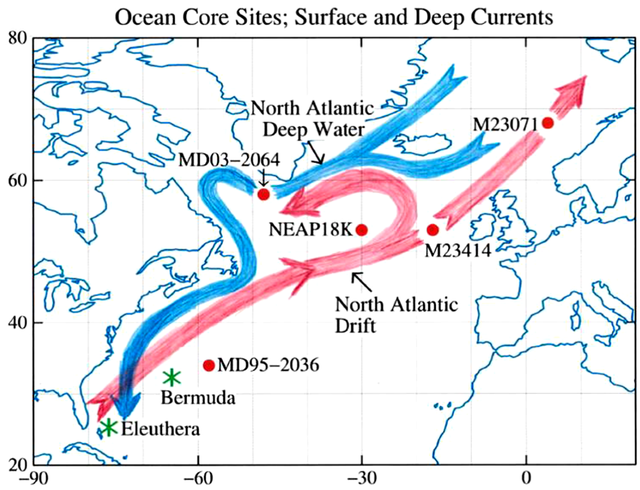


Figure 2. Ocean and ice core sites and simplified sketch of upper ocean North Atlantic Current and North Atlantic Deep Water return flow. In interglacial periods the North Atlantic Current extends further north, allowing the Greenland-Iceland-Norwegian Sea to become an important source of deepwater formation.

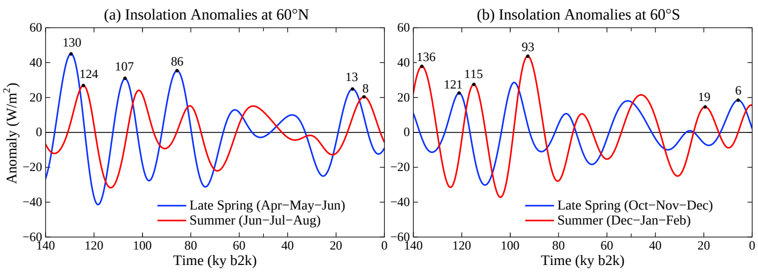


Figure 3. Summer (Jun–Jul–Aug) and late spring (Apr–May–Jun) insolation anomalies at 60° N and summer (Dec–Jan–Feb) and late spring (Oct–Nov–Dec) anomalies at 60° S.

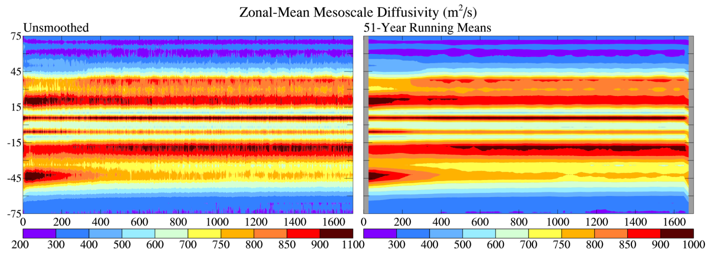


Figure 4. Control run zonal-mean mesoscale diffusivity versus time in 1700 year control run.

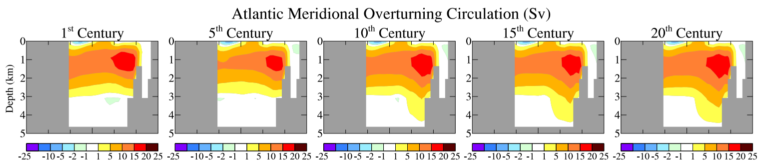


Figure 5. Atlantic Ocean mass stream function for the control run in its 1st, 5th, 10th, 15th and 20th centuries.

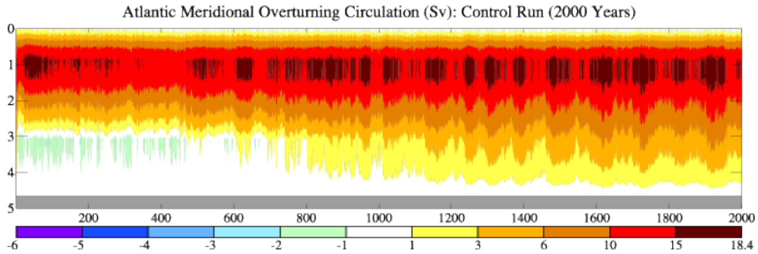


Figure 6. Annual mean Atlantic Ocean mass stream function at 28° N in the model control run.

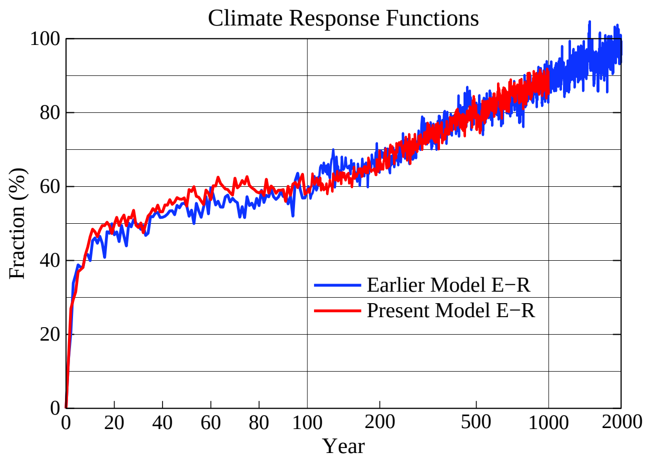


Figure 7. Climate response function, $R(t)$, i.e., the fraction of equilibriums surface temperature response for GISS model E-R based on a 2000 year control run (Hansen et al., 2007a). Forcing was instant CO_2 doubling with fixed ice sheets, vegetation distribution, and other long-lived GHGs.

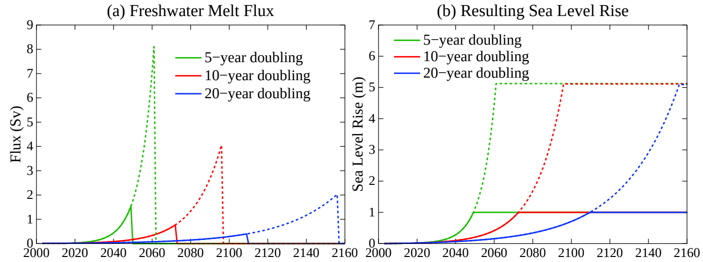


Figure 8. (a) total fresh water flux added in North Atlantic and Southern Oceans, **(b)** resulting sea level rise. Solid lines for 1 m sea level rise, dotted for 5 m. One Sverdrup (Sv) is $10^6\,m^3\,s^{-1}$, which is $\sim 3 \times 10^4\,Gt\,yr^{-1}$.

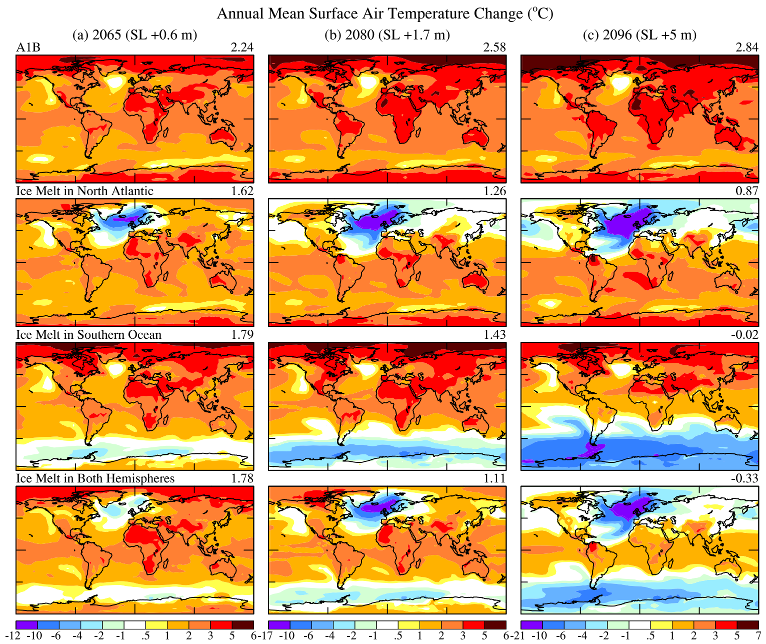


Figure 9. Surface air temperature relative to 1880–1920 in **(a)** 2065, **(b)** 2080, and **(c)** 2096. Top row is IPCC scenario A1B. Ice melt with 10 year doubling is added in other scenarios.

Exhibit 3 to Declaration of Dr. James E. Hansen

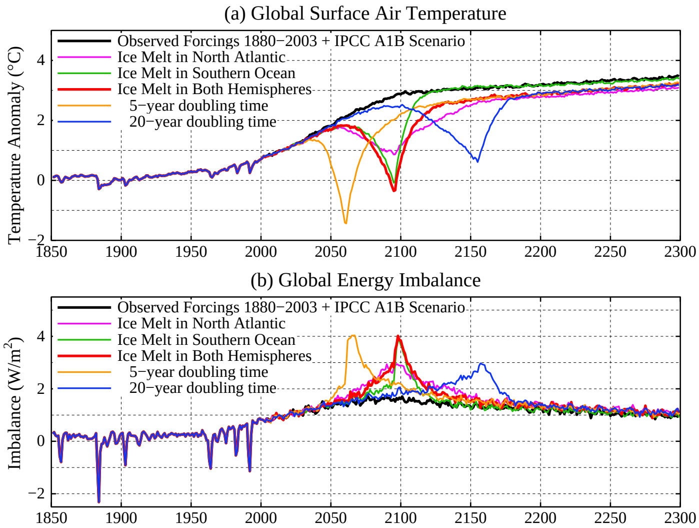


Figure 10. (a) Surface air temperature relative to 1880–1920 for several scenarios. **(b)** Global energy imbalance for the same scenarios.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

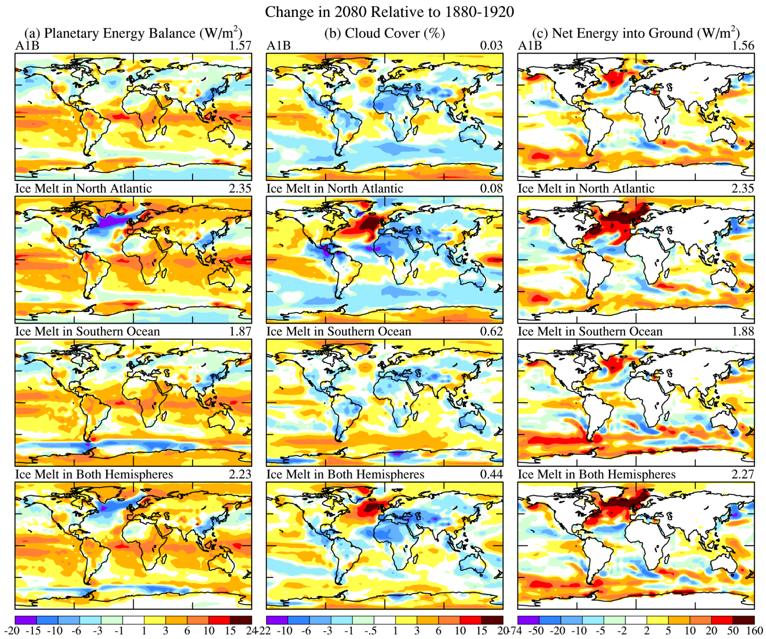


Figure 11. Change in 2078–2082, relative to 1880–1920, of the annual mean **(a)** planetary energy balance, **(b)** cloud cover, and **(c)** net energy into the ground, for the same four scenarios as in Fig. 9.

Exhibit 3 to Declaration of Dr. James E. Hansen

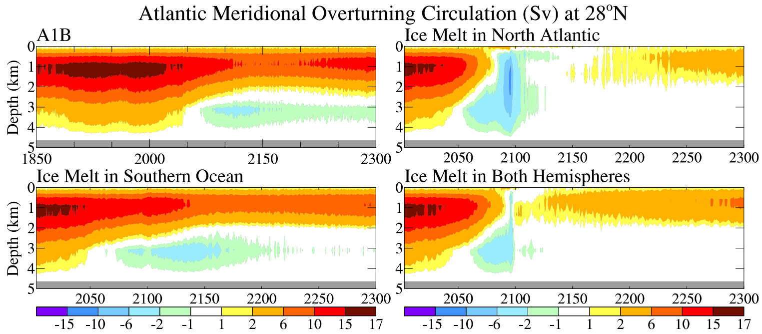


Figure 12. Ensemble-mean AMOC at 28° N versus time for the same four scenarios as in Fig. 9, with ice melt reaching 5 m at the end of the 21st century in the three experiments with ice melt.

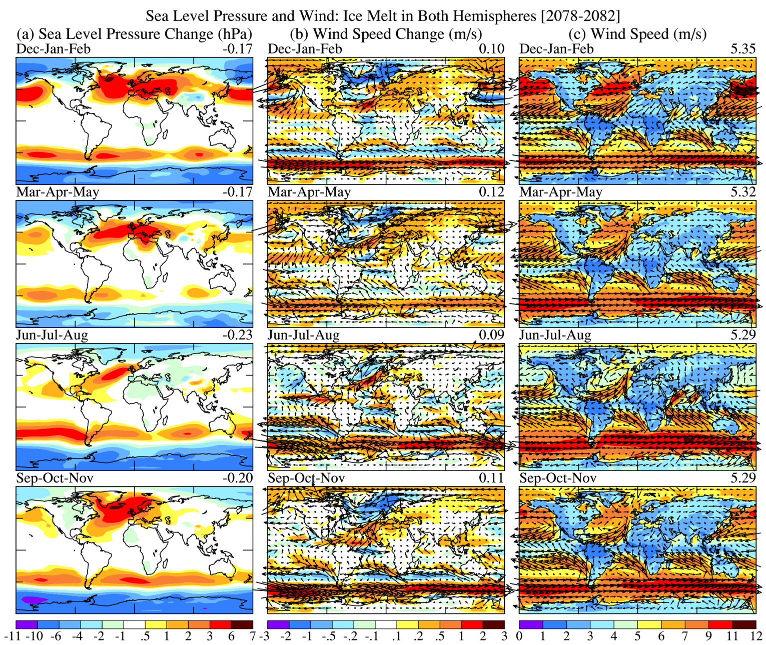


Figure 13. Change of seasonal mean **(a)** sea level pressure and **(b)** wind speed in 2078–2082 relative to 1880–1920, and **(c)** the wind speed itself, all for the scenario with ice melt in both hemispheres.

Exhibit 3 to Declaration of Dr. James E. Hansen

Exhibit A 119

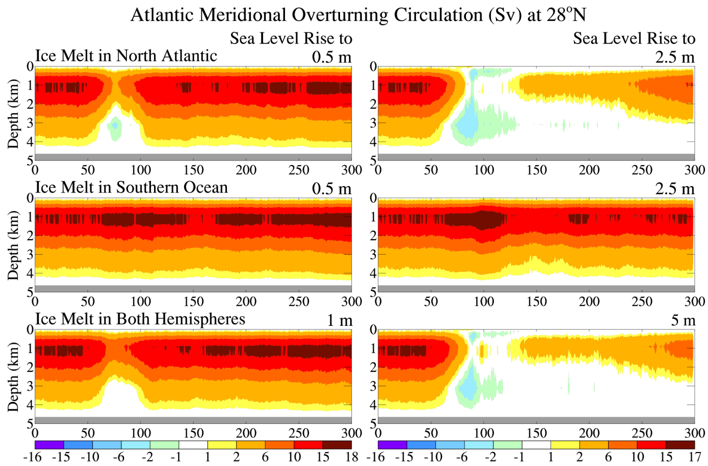


Figure 14. Ensemble-mean AMOC at 28° N versus time for six pure freshwater forcing experiments.

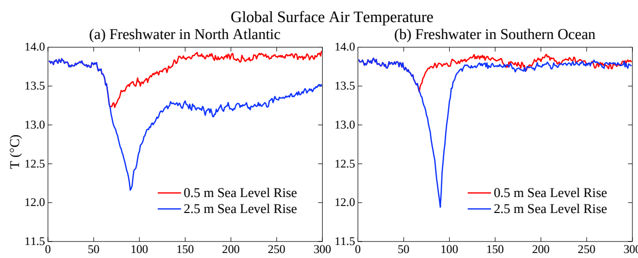


Figure 15. Ensemble-mean global surface air temperature for experiments (years on *x* axis) with freshwater forcing in either the North Atlantic Ocean (left) or the Southern Ocean (right).

Exhibit 3 to Declaration of Dr. James E. Hansen

Exhibit A 120

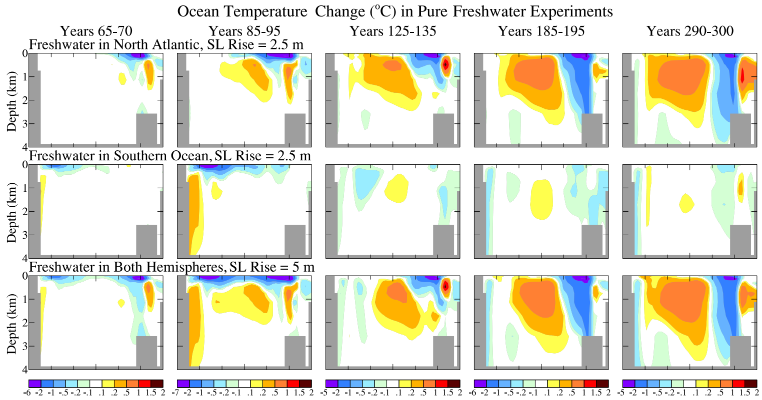


Figure 16. Change of ocean temperature relative to control run due to freshwater input that reaches 2.5 m of global sea level in a hemisphere (thus 5 m sea level rise in the bottom row).

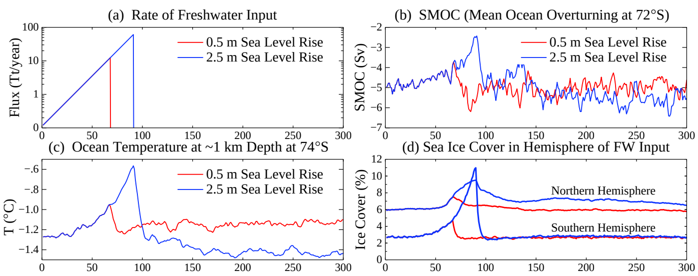


Figure 17. (a) Freshwater input to Southern Ocean (1 Tt = 1000 $km^3\ yr^{-1}$). **(b, c, d)** Simulated overturning strength (Sv) of AABW cell at 72° S, temperature at depth 1.13 km at 74° S, and hemispheric sea ice cover.

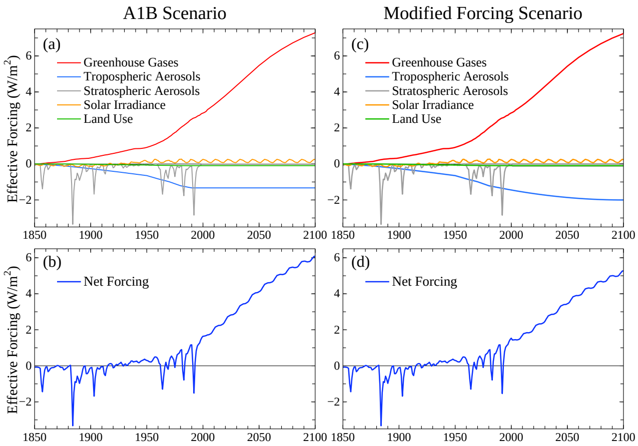


Figure 18. Effective global climate forcings in our climate simulations relative to values in 1850.

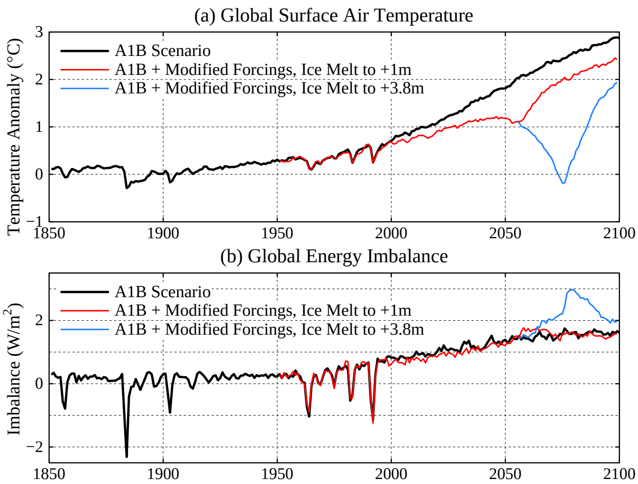


Figure 19. Surface air temperature change relative to 1880–1920 **(a)** and global energy imbalance **(b)** for the modified forcing scenario including cases with global ice melt allowed to reach 1 and 3.8 m.

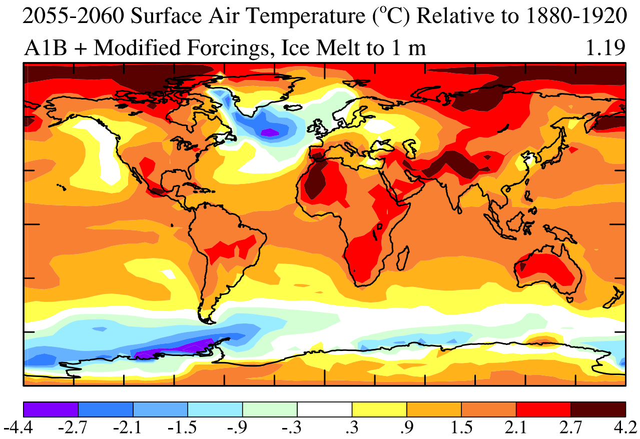


Figure 20. Surface air temperature change relative to 1880–1920 in 2055–2060 with the modified forcings.

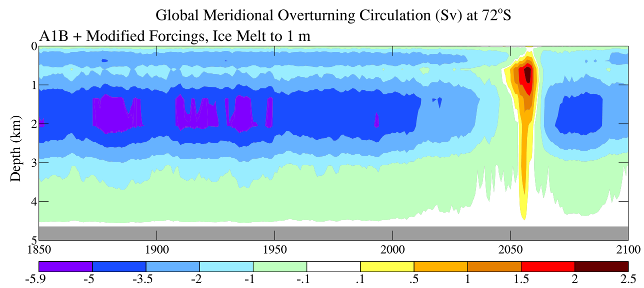


Figure 21. SMOC, ocean overturning strength at 72° S, including only the mean (Eularian) transport (Sect. 4.5). This is the average of a 5-member model ensemble for the modified forcing including advanced ice melt (720 Gt yr^{-1} from Antarctica in 2011) and 10 year doubling.

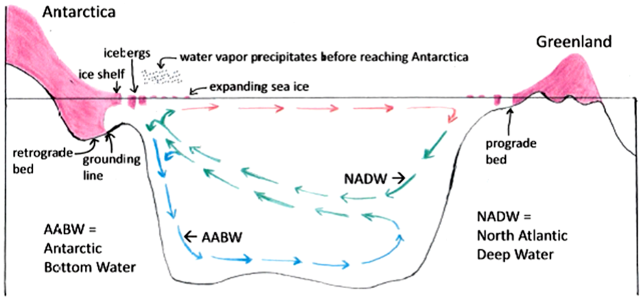


Figure 22. Schematic of stratification and precipitation amplifying feedbacks. Stratification: increased freshwater/iceberg flux increases ocean vertical stratification, reduces AABW formation, traps NADW heat, thus increasing ice shelf melting. Precipitation: increased freshwater/iceberg flux cools ocean mixed layer, increases sea ice area, causing increase of precipitation that falls before it reaches Antarctica, adding to ocean surface freshening and reducing ice sheet growth. A substantial amount of ice in West Antarctica and the Wilkes Basin, East Antarctica is vulnerable because of the reduced stability of retrograde beds.

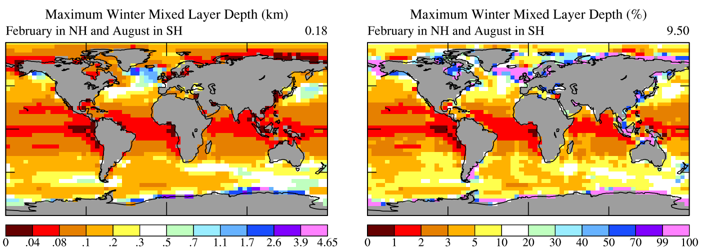


Figure 23. Maximum mixed layer depth (in km, left, and % of ocean depth, right) in February (Northern Hemisphere) and August (Southern Hemisphere) using the mixed layer definition of Heuze et al. (2013).

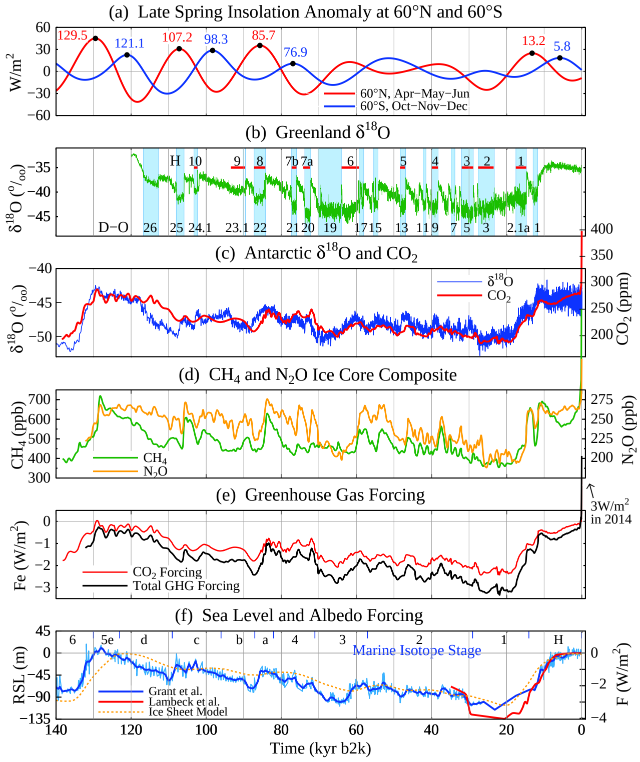


Figure 24. (a) Late spring insolation anomalies relative to the mean for the past million years, **(b)** $\delta^{18}O_{ice}$ of composite Greenland ice cores (Rassmussen et al., 2014) with Heinrich events of Guillevic et al. (2014), **(c, d)** $\delta^{18}O_{ice}$ of EDML Antarctic ice core (Ruth et al., 2007), multi-ice core CO_2, CH_4, and N_2O based on spline fit with 1000 year cut-off (Schilt et al., 2010), scales are such that CO_2 and $\delta^{18}O$ means coincide and standard deviations have the same magnitude, **(e)** GHG forcings from equations in Table 1 of Hansen et al. (2000), but with the CO_2, CH_4, and N_2O forcings multiplied by factors 1.024, 1.60, and 1.074, respectively, to account for each forcing's "efficacy" (Hansen et al., 2005), with CH_4 including factor 1.4 to account for indirect effect on ozone and stratospheric water vapor, **(f)** sea level data from Grant et al. (2012) and Lambeck et al. (2014) and ice sheet model results from de Boer et al. (2010). Marine isotope stage boundaries from Lisiecki and Raymo (2005). **(b–e)** are on AICC2012 time scale (Bazin et al., 2013),

Exhibit 3 to Declaration of Dr. James E. Hansen

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

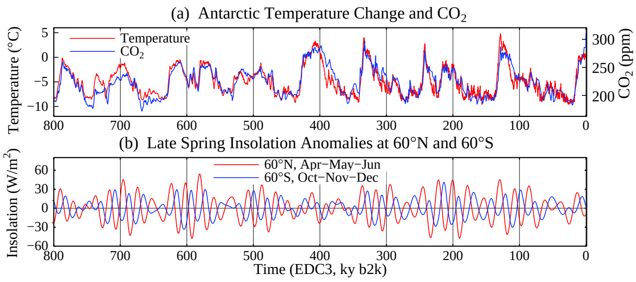


Figure 25. (a) Antarctic (Dome C) temperature relative to last 10 ky (Jouzel et al., 2007) on AICC2012 time scale and CO_2 amount (Luthi et al., 2008). Temperature scale is such that standard deviation of T and CO_2 are equal, yielding ΔT (°C) = 0.114 ΔCO_2 (ppm), **(b)** Late Spring insolation anomalies at 60° N and 60° S.

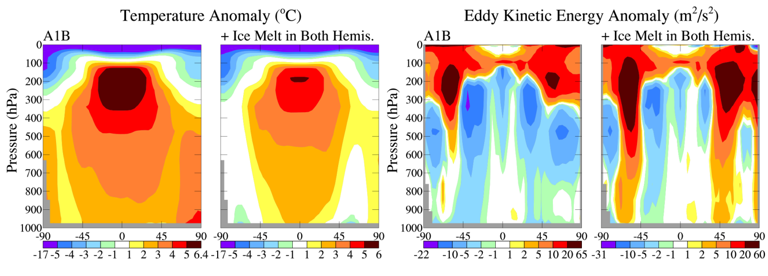


Figure 26. Simulated zonal mean temperature and eddy kinetic energy in 2078–2082 relative to 1880–1920 base period for A1B scenario and A1B plus 2.5 m ice melt in each hemisphere (simulations of Sect. 3).

Exhibit 3 to Declaration of Dr. James E. Hansen

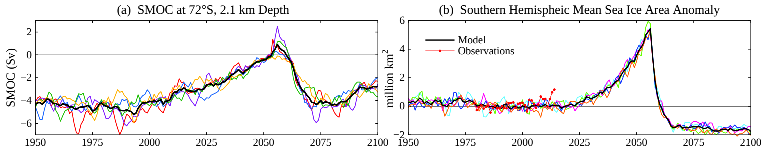


Figure 27. (a) SMOC, the global meridional overturning circulation at 72° S, in climate model runs including freshwater injection around Antarctica at a rate 720 Gt yr^{-1} in 2011, increasing with a 10 year doubling time, and half that amount around Greenland. SMOC diagnostic includes only the mean (Eulerian) term. **(b)** Annual-mean Southern Hemisphere sea ice area anomaly (relative to 1979–2000) in the five runs.

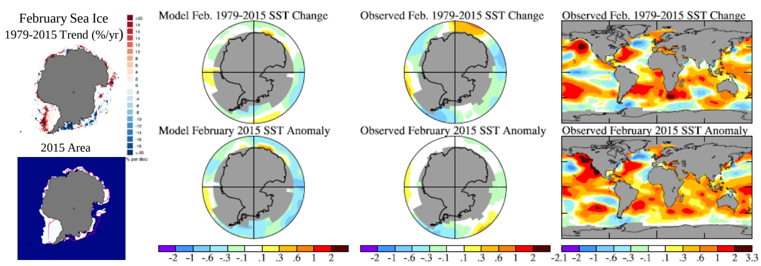


Figure 28. Observed February sea ice extent (left); modeled and observed SST near Antarctica and global. Upper: 1979–2015 change based on local linear trend. Lower: 2015 anomaly relative to 1951–1980. Sea ice data is update of Fetterer et al. (2002), temperature data is update of Hansen et al. (2010).

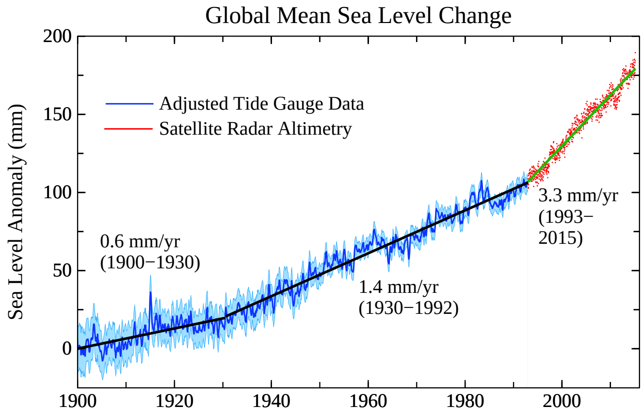


Figure 29. Sea level change based on satellite altimetry data (Nerem et al., 2010, updated at http://sealevel.colorado.edu) and tide gauge data (Church and White, 2011) with the latter change rate multiplied by 0.78, as required to yield a mean 1901–1990 change rate 1.2 mm yr^{-1} (Hay et al., 2015).